ERDC/CHL TR-09-17

Coastal and Hydraulics Laboratory

US Army Corps of Engineers®
Engineer Research and Development Center

Numerical Model Study of the Tuscarawas River below Dover Dam, Ohio

Richard L. Stockstill and Jane M. Vaughan

September 2009

ERDC/CHL TR-09-17
September 2009

Numerical Model Study of the Tuscarawas River below Dover Dam, Ohio

Richard L. Stockstill and Jane M. Vaughan

Coastal and Hydraulics Laboratory
U.S. Army Engineer Research and Development Center
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

Final report

Prepared for U.S. Army Engineer District, Huntington
502 8th Street
Huntington, WV 25701-2070

Abstract: The U.S. Army Corps of Engineers, Huntington District (LRH) has been charged with upgrading Dover Dam to meet hydrologic design standards and address stability issues. The LRH requested that the U. S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory (CHL), evaluate the flow conditions in the Tuscarawas River downstream of Dover Dam as part of a safety assurance program. The two-dimensional depth-averaged module of the Adaptive Hydraulics (ADH) finite element flow solver was used to obtain velocity information and water-surface elevations. This report provides water-surface elevations, velocity data, and flow patterns for flows varying from 8,900 cfs to the Probable Maximum Flood of 207,000 cfs. These flows may cause bank erosion downstream of the stilling basin under existing conditions. District engineers will use the information gathered from this study to design bank protection below the dam.

Contents

Figures and Tables iv

Preface vii

Unit Conversion Factors viii

1 Introduction 1
- Background 1
- Purpose 2

2 Numerical Model 5
- Adaptive Hydraulics (ADH) Code 5
- Computational Meshes 6
- Boundary Conditions 11

3 Results 15
- Flow Condition 1 15
- Flow Condition 2 16
- Flow Condition 3 16
- Flow Condition 4 16
- Flow Condition 5 17
- Flow Condition 6, PMF 17
- Flow Condition 7 18

4 Summary 47

References 48

Report Documentation Page

Figures and Tables

Figures

Figure 1. Vicinity map showing location of Dover Dam 2
Figure 2. As-Built plan of Dover Dam 3
Figure 3. Flow through Dover Dam sluices 3
Figure 4. Right bank of Tuscarawas River looking downstream of Dover Dam 4
Figure 5. Left bank of Tuscarawas River looking downstream of Dover Dam 4
Figure 6. Details of original computational mesh with bed contours and plan of Dover Dam 7
Figure 7. Details of larger computational mesh used for simulation of high discharges 8
Figure 8. Model limits (white) and contours at el 860, el 870 and el 880 9
Figure 9. Computational mesh created from survey data (green and yellow), 1D model cross-sections (blue), and aerial photograph (obtained from maps.live.com) 10
Figure 10. Detail of computational mesh stilling basin sections and inflow locations 12
Figure 11. Velocity magnitude contours, flow Condition 1, discharge 23,500 cfs, stilling basin tailwater el 881.2 19
Figure 12. Velocity magnitude contours and stream traces downstream of Dover Dam, flow Condition 1, discharge 23,500 cfs, stilling basin tailwater el 881.2 20
Figure 13. Water surface contours and vectors, flow Condition 1, discharge 23,500 cfs, stilling basin tailwater el 881.2 20
Figure 14. Water depth contours, flow Condition 1, discharge 23,500 cfs, stilling basin tailwater el 881.2 21
Figure 15. Velocity magnitude contours, flow Condition 2, discharge 38,000 cfs, stilling basin tailwater el 885.3 22
Figure 16. Velocity magnitude contours and stream traces downstream of Dover Dam, flow Condition 2, discharge 38,000 cfs, stilling basin tailwater el 885.3 23
Figure 17. Water surface contours and vectors, flow Condition 2, discharge 38,000 cfs, stilling basin tailwater el 885.3 23
Figure 18. Water depth contours, flow Condition 2, discharge 38,000 cfs, stilling basin tailwater el 885.3 24
Figure 19. Velocity magnitude contours, flow Condition 3, discharge 42,000 cfs, stilling basin tailwater el 886.3 25
Figure 20. Velocity magnitude contours and stream traces downstream of Dover Dam, flow Condition 3, discharge 42,000 cfs, stilling basin tailwater el 886.3 26
Figure 21. Water surface contours and vectors, flow Condition 3, discharge 42,000 cfs, stilling basin tailwater el 886.3 26
Figure 22. Water depth contours, flow Condition 3, discharge 42,000 cfs, stilling basin tailwater el 886.3 27
Figure 23. Velocity magnitude contours, flow Condition 4, discharge 72,500 cfs, stilling basin tailwater el 892.4 28

Figure 24. Velocity magnitude contours and stream traces downstream of Dover Dam, flow Condition 4, discharge 72,500 cfs, stilling basin tailwater el 892.4 29

Figure 25. Water surface contours and vectors, flow Condition 4, discharge 72,500 cfs, stilling basin tailwater el 892.4.......... 29

Figure 26. Water depth contours, flow Condition 4, discharge 72,500 cfs, stilling basin tailwater el 892.4 30

Figure 27. Velocity magnitude contours, flow Condition 5, discharge 125,000 cfs, stilling basin tailwater el 898.5.......... 31

Figure 28. Velocity magnitude contours and stream traces downstream of Dover Dam, flow Condition 5, discharge 125,000 cfs, stilling basin tailwater el 898.5.......... 32

Figure 29. Water surface contours and vectors, flow Condition 5, discharge 125,000 cfs, stilling basin tailwater el 898.5.......... 32

Figure 30. Water depth contours, flow Condition 5, discharge 125,000 cfs, stilling basin tailwater el 898.5 33

Figure 31. Contour lines at el 865, el 877, and el 889 34

Figure 32. Velocity magnitude profile at el 865, Condition 5, discharge 125,000 cfs, stilling basin tailwater el 898.5 (left and right are referenced to looking downstream) 35

Figure 33. Velocity magnitude profile at el 877, Condition 5, discharge 125,000 cfs, stilling basin tailwater el 898.5 (left and right are referenced to looking downstream) 36

Figure 34. Velocity magnitude profile at el 889, Condition 5, discharge 125,000 cfs, stilling basin tailwater el 898.5 (left and right are referenced to looking downstream) 37

Figure 35. Velocity magnitude contours, flow Condition 6 (PMF), discharge 207,000 cfs, stilling basin tailwater el 907.0 38

Figure 36. Velocity magnitude contours and stream traces downstream of Dover Dam, flow Condition 6 (PMF), discharge 207,000 cfs, stilling basin tailwater el 907.0.......... 39

Figure 37. Water surface contours and vectors, flow Condition 6 (PMF), discharge 207,000 cfs, stilling basin tailwater el 907.0 39

Figure 38. Water depth contours, flow Condition 6 (PMF), discharge 207,000 cfs, stilling basin tailwater el 907.0 40

Figure 39. Velocity magnitude profile at el 865, Condition 6, discharge 207,000 cfs, stilling basin tailwater el 907.0 (left and right are referenced to looking downstream).......... 41

Figure 40. Velocity magnitude profile at el 877, Condition 6, discharge 207,000 cfs, stilling basin tailwater el 907.0 (left and right are referenced to looking downstream).......... 42

Figure 41. Velocity magnitude profile at el 889, Condition 6, discharge 207,000 cfs, stilling basin tailwater el 907.0 (left and right are referenced to looking downstream).......... 43

Figure 42. Velocity magnitude contours, Condition 7, discharge 8,900 cfs, stilling basin tailwater el 874.1.......... 44

Figure 43. Velocity magnitude contours and stream traces downstream of Dover Dam, flow Condition 7, discharge 8,900 cfs, stilling basin tailwater el 874.1 45

Figure 44. Water surface contours and vectors, flow Condition 7, discharge 8,900 cfs, stilling basin tailwater el 874.1 45

Figure 45. Water depth contours, flow Condition 7, discharge 8,900 cfs, stilling basin tailwater el 874.1.......... 46

Tables

Table 1. Flow conditions simulated. 11
Table 2. Head loss along channel. 14
Table 3. Numerical model results. 15

Preface

The investigation reported herein was authorized and funded by the U. S. Army Engineer District, Huntington (LRH). This work was conducted in the Coastal and Hydraulics Laboratory (CHL) of the U.S. Army Engineer Research and Development Center (ERDC) during the period of July 2008 to October 2008 under the general direction of Thomas W. Richardson, Director of the CHL; Dr. Rose Kress, Chief of the Navigation Division, CHL; and Dennis W. Webb, Chief of the Navigation Branch, CHL.

This investigation was conducted by Dr. Richard L. Stockstill and Jane M. Vaughan of the Navigation Branch, CHL. Acknowledgments are made to Kenneth C. Halstead, LRH for his guidance in this study. Dr. Stephen T. Maynord provided a peer review of the report.

At the time of this report, COL Gary E. Johnston was Commander and Executive Director of ERDC. Dr. James R. Houston was Director.

Unit Conversion Factors

Multiply	By	To Obtain
cubic feet	0.02831685	cubic meters
feet	0.3048	meters
miles (U.S. statute)	1,609.347	meters

1 Introduction

Background

Dover Dam is located in Tuscarawas County, Ohio, on the Tuscarawas River, approximately 3.5 miles northeast of Dover, Ohio, as shown in Figure 1. Dover Dam is a concrete gravity structure with a maximum height of 83 ft above the streambed. The overall length of the dam is 824 ft at elevation 931[1]. An uncontrolled ogee spillway is situated in the center channel section. The crest length is 338 ft at el 916. Eighteen gate-controlled sluices, located at the base of the spillway, make up the outlet works. They are arranged in groups of six at three different levels. The stilling basin is divided into three sections, each at a different elevation corresponding to the three groups of conduits in the spillway section. The stilling basin consists of a stepped apron with training walls between three sections and a system of baffle piers. A plan of Dover Dam is presented in Figure 2 and a photograph in Figure 3.

Inspections of Dover Dam have revealed significant safety concerns. The Corps of Engineers has determined that the dam cannot accommodate the theoretical Probable Maximum Flood (PMF). The dam also has stability issues related to known faulting and inadequate bedrock foundation. The U. S. Army Corps of Engineers, Huntington District (LRH) has been charged with upgrading Dover Dam to meet hydrologic design standards and address stability issues. The LRH requested that the U. S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory (CHL), evaluate the flow conditions in the Tuscarawas River downstream of Dover Dam as part of a safety assurance program. Flow conditions were modeled from the end sill of the Dover Dam stilling basin downstream to USGS stream gage 03122500, a distance of approximately 2.3 miles. The area 200 ft immediately downstream of the dam was of particular interest to this study. Photographs of the river banks downstream of the dam can be seen in Figures 4 and 5.

[1] All elevations (el) are in feet referenced to National Geodetic Vertical Datum.

Figure 1. Vicinity map showing location of Dover Dam.

Purpose

The purpose of the study was to determine flow velocities and patterns downstream of the dam during high spillway flows. Such flows may cause bank erosion downstream of the stilling basin under existing conditions. For this reason, some type of bank protection will be necessary. This report provides water-surface elevations, velocity data, and flow patterns for flows varying from 8,900 cfs to the Probable Maximum Flood of 207,000 cfs. District engineers will use the information gathered from this study to design bank protection below the dam.

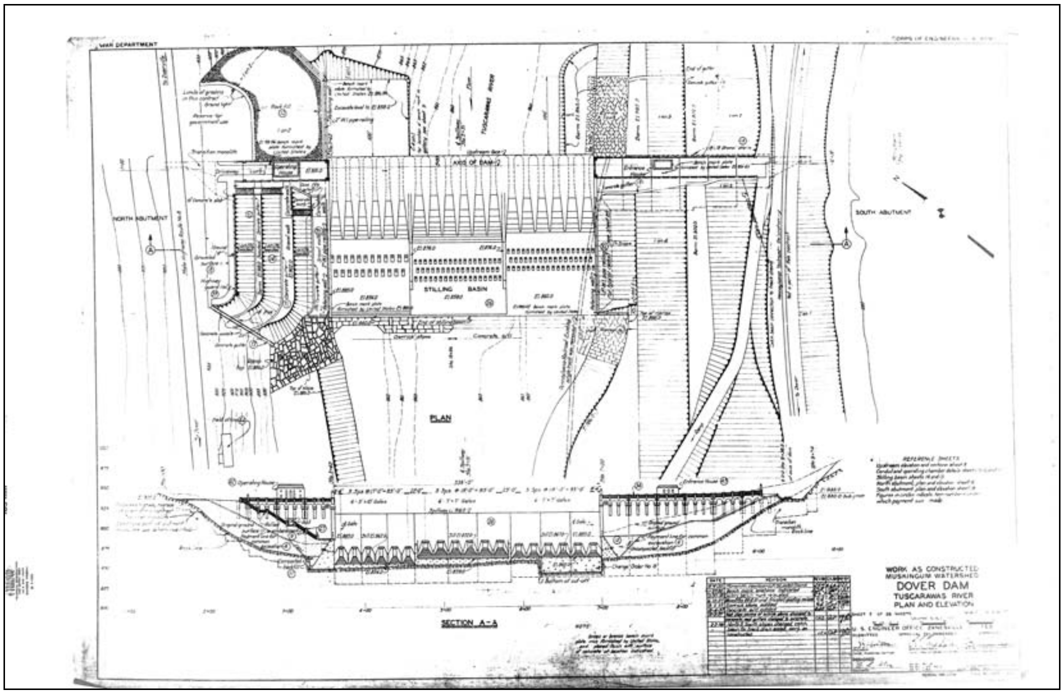

Figure 2. As-Built plan of Dover Dam.

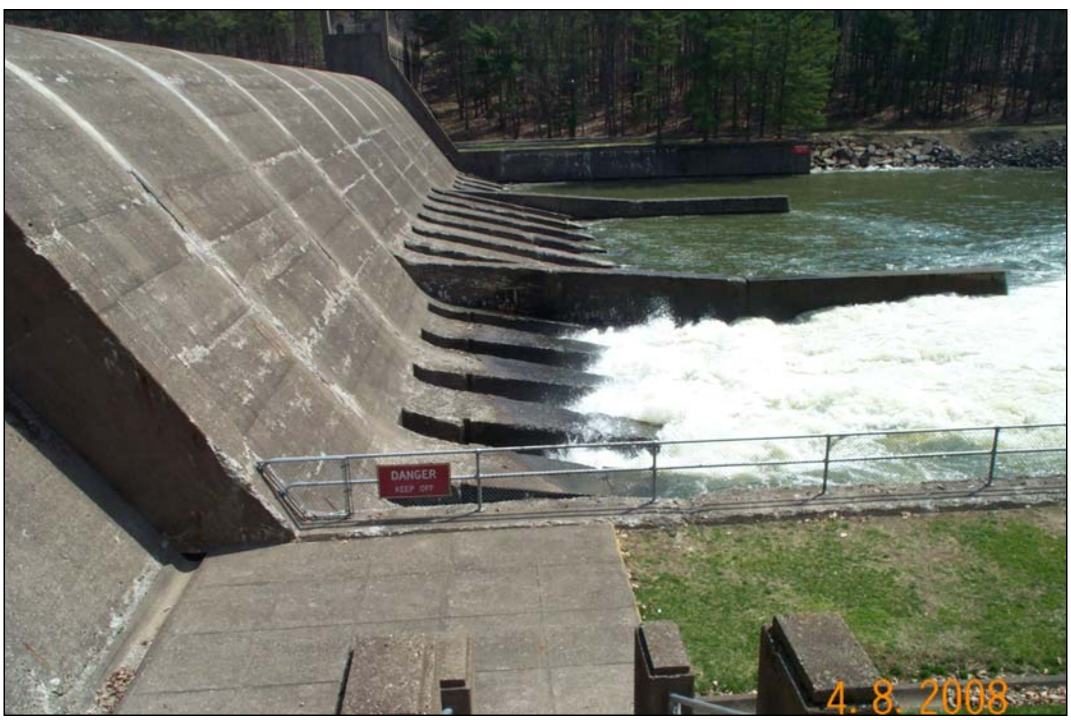

Figure 3. Flow through Dover Dam sluices.

Figure 4. Right bank of Tuscarawas River looking downstream of Dover Dam.

Figure 5. Left bank of Tuscarawas River looking downstream of Dover Dam.

2 Numerical Model

Adaptive Hydraulics (ADH) Code

The numerical model is the two-dimensional (2D) module of the Adaptive Hydraulics (ADH) finite element flow solver (http://adh.usace.army.mil/). This code, which was developed by the CHL, features mesh adaption whereby the computational mesh is automatically refined in areas where it is needed to provide an accurate solution.

The 2D flow model solves the shallow-water equations, which are a result of the vertical integration of the equations of mass and momentum conservation for incompressible flow under the hydrostatic pressure assumption. The flow depth (h), the x-component of velocity (u), and the y-component of velocity (v) define the dependent variables of the fluid motion. The model equations are given as:

$$\frac{\partial \mathsf{U}}{\partial t}+\frac{\partial \mathsf{F}}{\partial x}+\frac{\partial \mathsf{G}}{\partial y}+\mathsf{H}=0 \tag{1}$$

where:

$$\mathsf{U}=\begin{Bmatrix} h \\ uh \\ vh \end{Bmatrix} \tag{2}$$

$$\mathsf{F}=\begin{Bmatrix} hu \\ hu^2+\frac{1}{2}gh^2-h\dfrac{\sigma_{xx}}{\rho} \\ huv-h\dfrac{\sigma_{yx}}{\rho} \end{Bmatrix} \tag{3}$$

$$\mathbf{G} = \begin{Bmatrix} hv \\ huv - h\dfrac{\sigma_{xy}}{\rho} \\ hv^2 + \frac{1}{2}gh^2 - h\dfrac{\sigma_{yy}}{\rho} \end{Bmatrix} \tag{4}$$

and:

$$\mathbf{H} = \begin{Bmatrix} 0 \\ gh\dfrac{\partial z_b}{\partial x} + n^2 g\dfrac{u\sqrt{u^2+v^2}}{C_0 h^{1/3}} \\ gh\dfrac{\partial z_b}{\partial y} + n^2 g\dfrac{v\sqrt{u^2+v^2}}{C_0 h^{1/3}} \end{Bmatrix} \tag{5}$$

Here:

ρ = the fluid density
g = gravitational acceleration
z_b = the channel bed elevation
n = the Manning's roughness coefficient
C_o = a dimensional constant (C_o = 1 for SI units and 2.208 for US Customary units)

and:

σ 's= the Reynolds stresses due to turbulence, where the first subscript indicates the direction, and the second indicates the face on which the stress acts.

The equations are discretized using the finite element method in which u, v, and h are represented as linear polynomials on each element.

Computational Meshes

The 2D computational meshes were generated using the Surface-water Modeling System (SMS) (http://chl.erdc.usace.army.mil/sms). Cross-sections from a

HEC-RAS model provided by the district, along with aerial photographs for proper alignment, were used to create the downstream river bathymetry. The LRH had a field survey performed to provide more detailed bathymetric information for the area 200 ft immediately downstream of the stilling basin.

Two computational meshes were used in this study. The first mesh consisted of 7,596 nodes and 14,659 triangular elements. It extended from 50 ft upstream of the stilling basin end sill to U. S. Geological Survey gage 03122500, which is located approximately 2.3 miles downstream of Dover Dam on the State Highway 416 bridge. Element sizes ranged from 3 ft by 6 ft at the stilling basin to 100 ft by 60 ft at the downstream end of the model. In the area around and just downstream of the dam, the element sizes were relatively small, to capture the detailed bed elevation data provided by the district. Details of the upstream end of the mesh are shown in Figure 6.

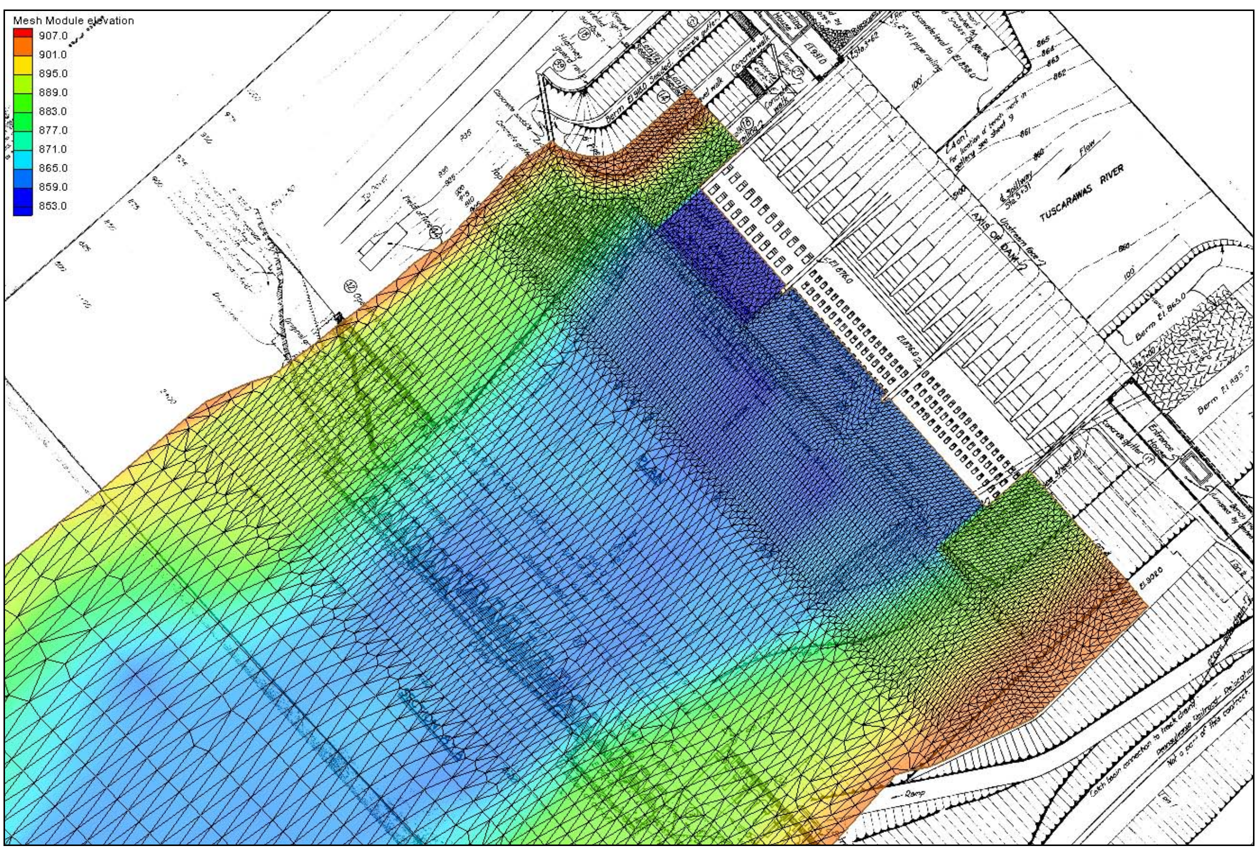

Figure 6. Details of original computational mesh with bed contours and plan of Dover Dam.

District personnel visited CHL on 23 and 24 September 2008 to discuss preliminary model results. During these discussions, it became clear that the original mesh did not cover enough of the areas of concern on each side of the stilling basin. During high discharge flows, the areas to the sides of the stilling basin contain large eddies that the original mesh could not capture because it did not reproduce enough of the overbank area. A mesh was needed that included the side areas extending all the way to the face of the dam. This area was added to the original mesh, enlarging it to a total of 8,340 nodes and 16,095 elements. The two largest flows, the probable maximum flood (207,000 cfs) and the 125,000 cfs discharge, were then simulated on the larger mesh. Details of the upstream end of this expanded mesh are shown in Figure 7. The entire extent of both meshes, with contours, cross-sections, elements, and survey data are shown in Figures 8 and 9.

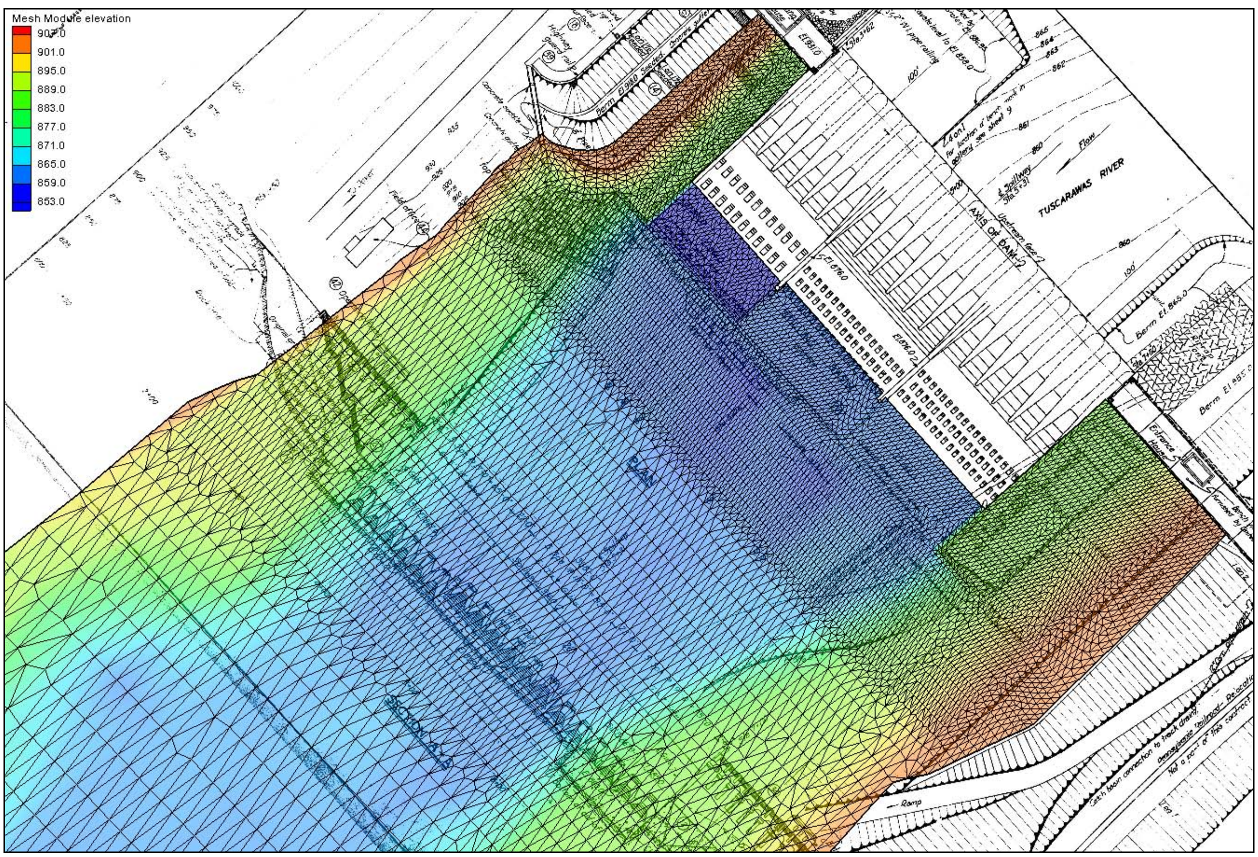

Figure 7. Details of larger computational mesh used for simulation of high discharges.

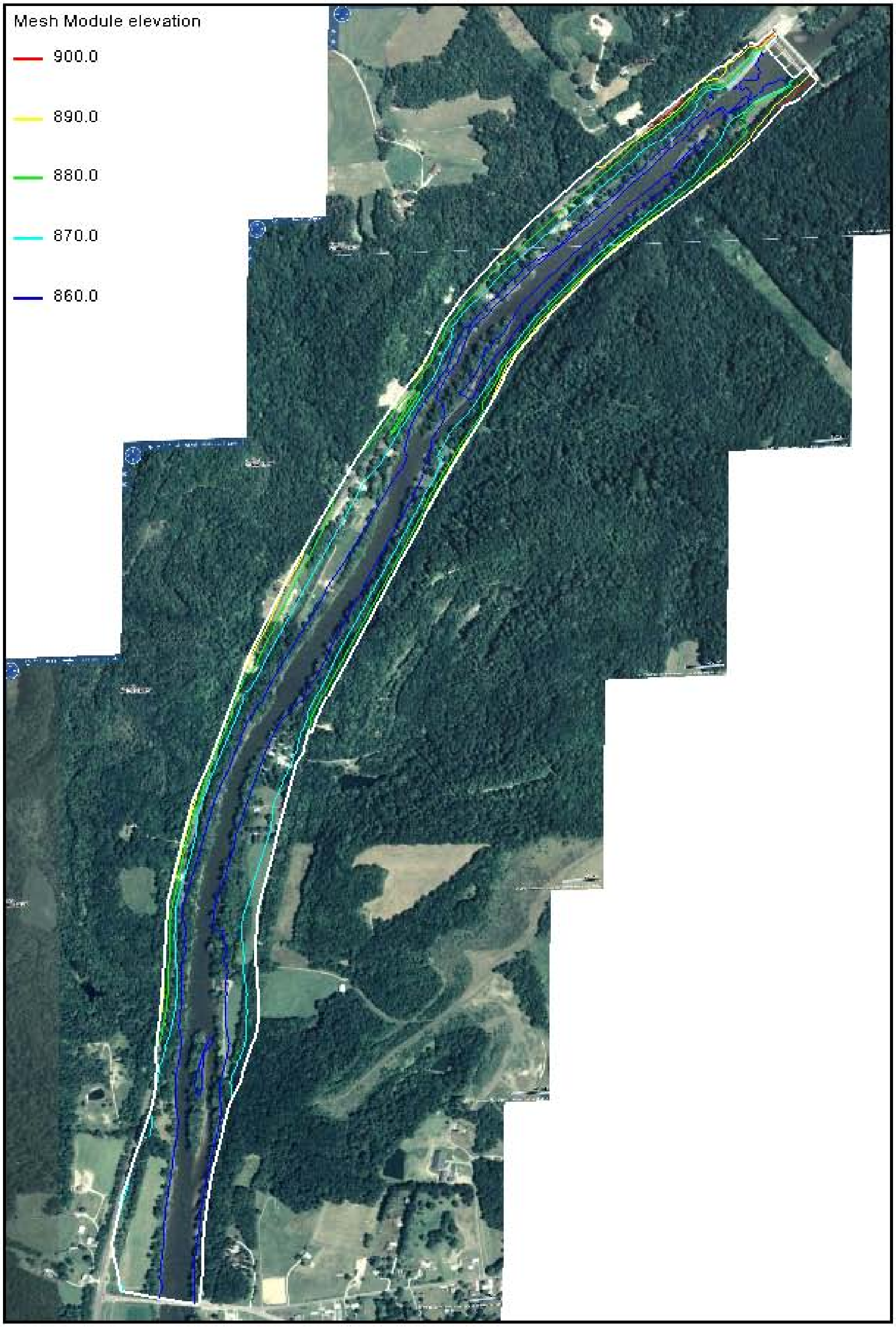

Figure 8. Model limits (white) and contours at el 860, el 870 and el 880.

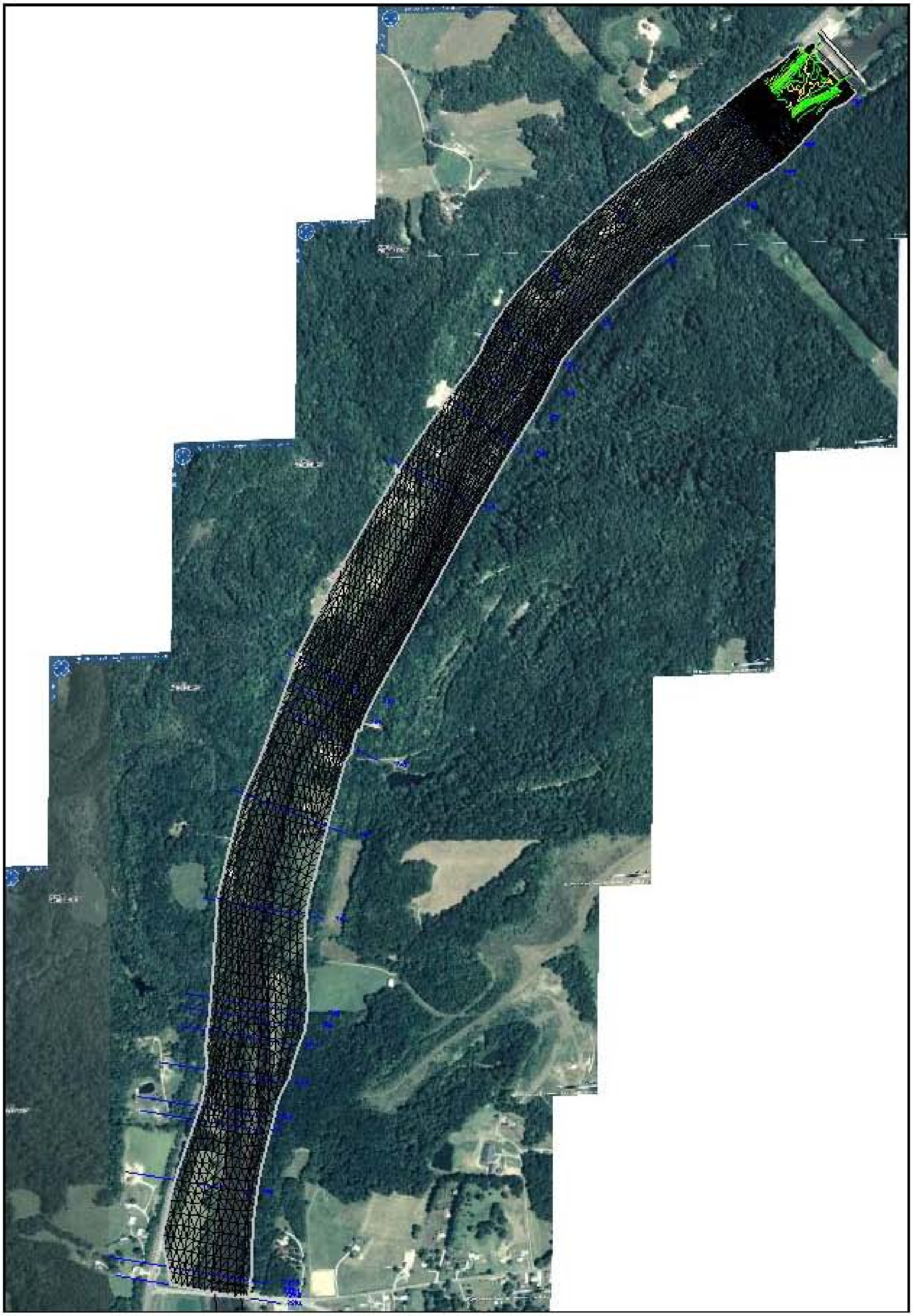

Figure 9. Computational mesh created from survey data (green and yellow), 1D model cross-sections (blue), and aerial photograph (obtained from maps.live.com).

The ADH code refines the mesh automatically by dividing the elements where the computed residual exceeds a specified threshold. To determine an appropriate refinement level and error tolerance, the Condition 1 (see Boundary Conditions for flow description) simulation was first run to steady state without using adaption. Then, the error output from this simulation was evaluated to determine the appropriate tolerance level for future runs. The levels of refinement, or how many times an element may be divided, was set by gradually increasing the number of refinement levels until there was virtually no change in the solution. No difference was noticeable with four and eight levels of adaption, so the maximum level of refinement was set to four for all simulations.

Boundary Conditions

Discharge and tailwater values were provided by the LRH and are listed in Table 1. The inflow boundary was 50 ft upstream of the stilling basin end sill. The outflow boundary was located at the Highway 416 bridge. The tailwater elevations provided by the district are referred to as stilling basin tailwater elevations. They correspond to water-surface elevations at a station located 450 ft downstream of the crest.

Table 1. Flow conditions simulated.

Condition	Discharge (cfs)	Tailwater Elevation
1	23,500	881.2
2	38,000	885.3
3	42,000	886.3
4	72,500	892.4
5	125,000	898.5
6	207,000	907.0
7	8,900	874.1

Manning's roughness coefficient, n, was varied over the domain according to the material represented. A roughness coefficient of 0.014 was assigned for the concrete stilling basin, a value of 0.02 was assigned for the channel and grassy overbank areas, and a value of 0.03 was used for wooded areas. The roughness coefficients for the grassy and wooded areas are on the low side of expected values, but were chosen because the purpose of this study

was to evaluate bank erosion potential. Low values of roughness coefficients result in relatively high computed velocities.

The total flow rate was input to the model by specifying equal unit discharge for each spillway stilling basin section (Figure 10). A unit discharge, total discharge divided by spillway width, was specified as the inflow for each of the three sections. Section 1 was 102 ft long and sections 2 and 3 were each 114 ft long, summing to a total inflow length of 330 ft. The model was run from an initial condition assuming zero velocity and a constant water-surface elevation. The unit discharge was set as the inflow boundary condition and the outflow boundary consisted of a specified tailwater elevation. The model was run to steady state by advancing in time until the solution did not vary with additional time steps.

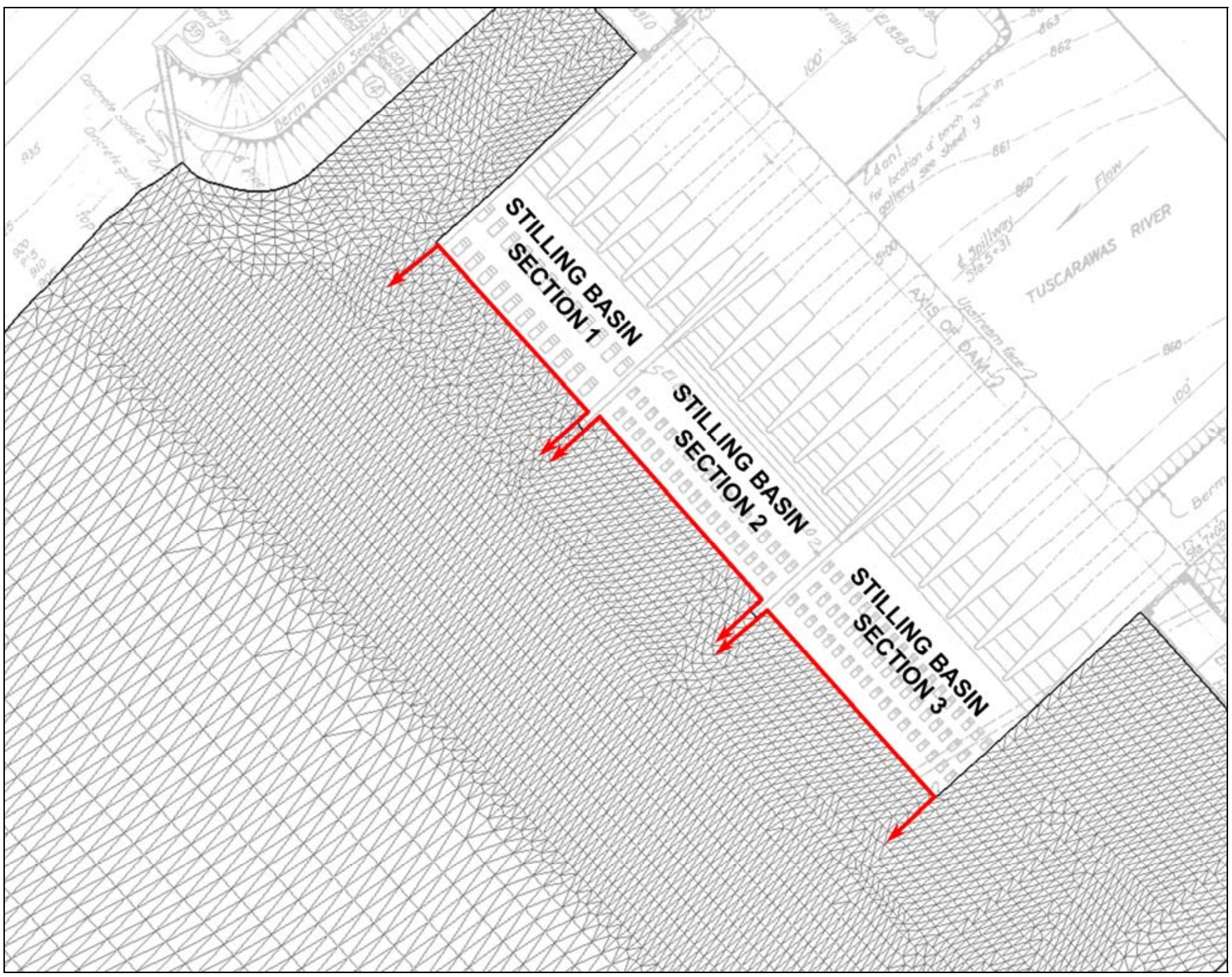

Figure 10. Detail of computational mesh stilling basin sections and inflow locations.

The LRH provided water-surface elevations at the stilling basin for each flow condition (Table 1). The water-surface elevation at the outflow boundary was adjusted so that the computed water-surface elevations matched those provided by the district. For each flow condition, a water-surface elevation was assumed at the downstream end of the model. The model was then run to steady state and the water-surface elevation at the stilling basin tailwater location was compared to the elevation provided by the LRH. If the water-surfaces were not equal, the outflow tailwater elevation was adjusted, the model was again run to steady state, and the water-surface elevations were compared. This iterative procedure was repeated until the difference in the simulated water-surface elevation and the district-supplied tailwater elevation was less than or equal to 0.1 ft.

The computed tailwaters are provided in Table 2. The head losses along the channel for each flow condition are also listed in Table 2. The velocity head is based on a cross-sectional average of discharge divided by the computed flow area. The total head is the sum of the water-surface elevation and the velocity head.

The boundaries defined by the water lines were different for each flow condition because of the side slopes along the banks. Each computational mesh included a large enough portion of the overbank area along the Tuscawaras River to contain the high flows. The water line moved up the side slopes as the discharge increased. The ADH code has the ability to turn elements on and off as they become wet or dry. So, the solution procedure includes determination of the domain limits since they are dependent on the water-surface elevation. The figures of model results show dry areas of each mesh as blank regions inside the model boundary.

Table 2. Head loss along channel.

Condition	Tailwater Location	Water - Surface Elevations	Velocity Head (ft)	Total Head	Head Loss Along Channel (ft)
1	Stilling basin	881.22	0.27	881.49	0.34
	Outflow	881.10	0.05	881.15	
2	Stilling basin	885.26	0.47	885.73	0.54
	Outflow	885.10	0.09	885.19	
3	Stilling basin	886.26	0.50	886.76	0.56
	Outflow	886.09	0.11	886.20	
4	Stilling basin	892.40	0.75	893.15	0.72
	Outflow	892.23	0.20	892.43	
5	Stilling basin	898.47	1.31	899.78	1.07
	Outflow	898.27	0.43	898.70	
6	Stilling basin	906.97	6.21	913.18	4.59
	Outflow	906.76	1.83	908.59	
7	Stilling basin	874.11	0.11	874.22	0.20
	Outflow	874.00	0.02	874.02	

3 Results

The results of all simulations are presented in Figures 11-45. The 2D model solutions provide variation over the domain of depth and depth-averaged velocity in each horizontal direction. The stilling basin tailwater location specified by the district is identified by a dashed line in the figures of velocity magnitude and water-surface elevation contours. The results are generalized in the depth-averaged velocities and water-surface elevations presented in Table 3. In general, the greater discharges resulted in higher velocities and higher water-surface elevations. Areas of flow circulation were found to exist near the channel edges. These eddies formed downstream of bank features such as channel expansions and bed elevation changes. The eddy patterns were particularly pronounced just below and to the sides of the stilling basin.

Table 3. Numerical model results.

Condition	Discharge (cfs)	Stilling Basin Tailwater Elevation	Outflow Tailwater Elevation	Maximum Depth-Averaged Velocity (fps)	Water -Surface Elevations
1	23,500	881.2	881.1	5.4	880.8-881.3
2	38,000	885.3	885.2	6.9	884.8-885.7
3	42,000	886.3	886.1	7.1	886.0-886.5
4	72,500	892.4	892.2	8.5	891.9-893.0
5	125,000	898.5	898.3	10.7	895.8-898.0
6	207,000	907.0	906.8	13.5	902.3-907.5
7	8,900	874.1	874.0	3.5	874.0-874.3

Flow Condition 1

The discharge for flow Condition 1 was 23,500 cfs. Figure 11 shows the velocity magnitude contours over the entire model along with tailwater elevations. Areas inside the model limits that are not contoured are dry overbank areas. The outflow tailwater was set to el 881.1 which gave a resulting stilling basin tailwater of el 881.2. The maximum velocities were in the 5 fps range and were concentrated in the center of the channel. The majority of the flow moved downstream at 3 to 4 fps. Small eddies formed

on either side just below the retaining wall as the flow exited the stilling basin. Eddies also formed along the sides of the channel well below the area of interest, as shown in Figure 12. The velocities in these areas ranged from 0.2 to 2 fps. The water surface, ranging from el 881 to el 882, and velocity vectors in the area immediately downstream of the stilling basin are presented in Figure 13. Depth contours ranging from 0 to 55 ft are shown in Figure 14.

Flow Condition 2

The discharge for flow Condition 2 was 38,000 cfs. The velocity distribution along the river is illustrated by the contours shown in Figure 15. An outflow tailwater of el 885.2 resulted in a stilling basin tailwater of el 885.3. The maximum velocities were about 6 fps. Generally, the velocity in the main channel was 5 to 6 fps. Similar to flow Condition 1, eddies formed on either side as the flow left the stilling basin and entered the areas behind each walls. Eddies also formed on either side of the channel 650 ft downstream of the dam, below the area of interest, as shown in Figure 16. The velocities in these areas ranged from 0.2 to 4 fps. Just downstream of the stilling basin, the water surface ranged from el 885 to el 886. Velocity vectors and water-surface elevations are presented in Figure 17. Contours of the water depth are shown in Figure 18.

Flow Condition 3

The discharge for flow Condition 3 was 42,000 cfs. The velocity magnitude contours and tailwater elevations are shown in Figure 19. Setting the outflow tailwater to el 886.1 resulted in a stilling basin tailwater of el 886.3. The maximum velocities were about 7 fps as shown in Figure 20. Eddies formed on either side, as with the lower discharges. The velocities in these areas ranged from 0.1 to 5 fps. The water surface varied from el 886 to el 886.5. Flow conditions immediately downstream of the stilling basin are shown with the water-surface contours and velocity vectors presented in Figure 21. Water depth contours are presented in Figure 22.

Flow Condition 4

Flow Condition 4 was 72,500 cfs and a stilling basin tailwater of el 892.4. The stilling basin water-surface elevation was accomplished by setting the outflow tailwater to el 892.2. Figure 23 shows the velocity magnitude contours along the entire model. The maximum velocities of about 8 fps

were concentrated in the center of channel. A pair of eddies formed on each side of the channel below the stilling basin, as shown in Figure 24. Larger circulations were established near either bank about 550 ft downstream of the stilling basin. The eddy on the right descending bank was the stronger. The water surface in the area immediately downstream of the stilling basin ranged from el 892 to el 893 and is shown along with velocity vectors in Figure 25. Figure 26 shows contours of the water depth.

Flow Condition 5

Flow Conditions 5 and 6 were the primary concerns for this study. The velocities over the banks were of particular interest. Since the expected high velocities in these areas raise the potential for erosion, these areas might require armoring. The discharge for flow Condition 5 was 125,000 cfs. Contours of velocity magnitude are provided in Figure 27. An outflow tailwater of el 898.3 produced a stilling basin tailwater of el 898.5. The maximum velocities ranged from 6 to 10 fps and were located much closer to the stilling basin than those seen with the lower flows. Eddies formed to the sides of the outside walls of the stilling basin, as shown in Figure 28. The velocities in these areas were as large as 5 fps. The water surface varied from el 898 to el 899. Contours of the water-surface elevation and velocity vectors in the area immediately downstream of the stilling basin are presented in Figure 29. Water depth contours are shown in Figure 30.

Velocities were extracted from model results along 1000-ft-long lines of constant bed elevation beginning at the stilling basin. Three lines were sampled on each side of the channel, at el 865, el 877, and el 889 (Figure 31). Velocity profiles along these lines are plotted in Figures 32-34. Velocities along el 865 were found to be in excess of 10 fps over the left descending bank (Figure 32). Peak velocities along el 877 were more than 12 fps (Figure 33). The velocities along el 889 were not as large as the lower elevations. Maximum velocities along el 889 were about 9 fps, as shown in Figure 34.

Flow Condition 6, PMF

The Probable Maximum Flood discharge of 207,000 cfs was the highest flow simulated. The PMF was designated flow Condition 6, the results of which are shown in Figures 35-41. Contours of velocity magnitude are plotted in Figure 35. Flow patterns and velocity magnitudes immediately downstream of the dam are shown in Figure 36. Note that the contour

scale of velocity magnitude for the PMF results is from 0 to 14 fps, whereas the contour range shown on figures of the other flow conditions is from 0 to 10 fps.

A stilling basin tailwater of el 907.0 was produced by setting an outflow tailwater of el 906.8. Velocities in the center of the channel were greater than 13 fps in the flow leaving the stilling basin. This flow did not slow to less that 10 fps until 850 ft downstream of the end sill. Even along the overbank, velocities reached up to 9 fps in some places, particularly on the left side of the channel. Large eddies formed on the sides of the stilling basin with velocities exceeding 8 fps in some areas, as shown in Figure 36. The water surface in the area immediately downstream of the stilling basin varied from el 906 to el 907. Contours of water surface and velocity vectors in this area are presented in Figure 37. Figure 38 shows water depth contours immediately downstream of the dam.

Profiles of velocities produced by the PMF were extracted from model results at el 865, el 877, and el 889 (Figure 31). The profiles are along lines of constant elevation and distance downstream of the stilling basin. The velocity profiles are provided in Figures 39-41. Along contour el 865, maximum velocities exceeded 12 fps on the left side of the channel. At el 877, the velocities over the left bank also exceeded 12 fps from about 250 to 350 ft downstream of the end sill. Maximum velocities at el 889 were 10 fps over the left bank from about 200 ft to 450 ft downstream of the end sill.

The flow within the stilling basin, produced by the PMF, will probably spill over the training walls. The 2D model was not capable of adequately reproducing the spillway flows and hydraulic conditions within the stilling basin. Modeling the interaction of the stilling basin flow with the circulating flow behind the walls would require a detailed three-dimensional model. Three-dimensional flow conditions such as these are generally studied with a physical model of the entire structure. However, even with the limitations of a 2D model, the results shown in Figures 36 and 37 provide sufficiently accurate velocity information in the area between the training walls and the waterlines.

Flow Condition 7

The smallest discharge modeled was 8,900 cfs and the flow distribution along the entire length of the model is shown in Figure 42. The outflow

tailwater was set to el 874.0, which gave a resulting stilling basin tailwater of el 874.1. The maximum velocities were in the 3 to 4 fps range, and were concentrated in a small area in the center of the channel. The only pronounced eddy that formed with the flow Condition 7 is on the right bank and is far downstream of the area of interest (Figure 43). Water-surface contours and velocity vectors in the area immediately downstream of the stilling basin are presented in Figure 44, and water depth contours are presented in Figure 45.

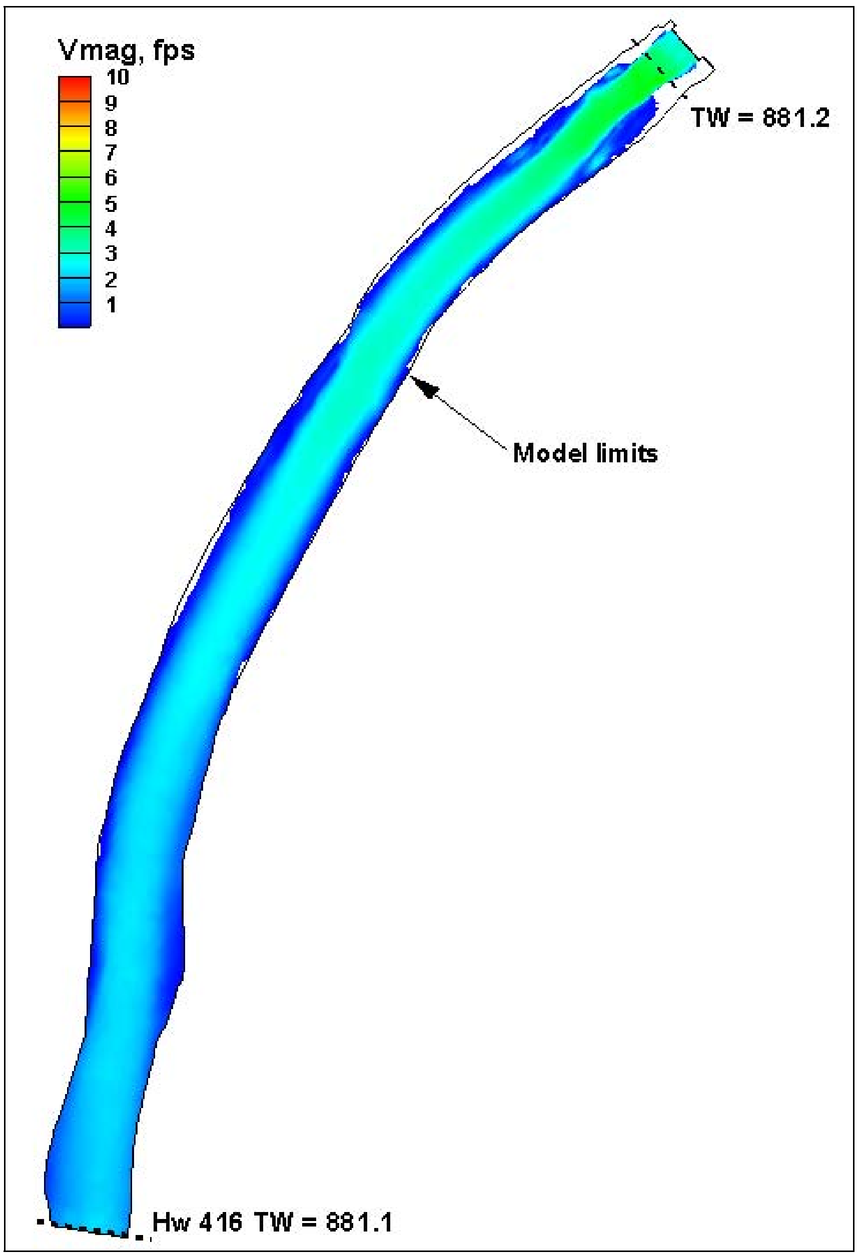

Figure 11. Velocity magnitude contours, flow Condition 1, discharge 23,500 cfs, stilling basin tailwater el 881.2.

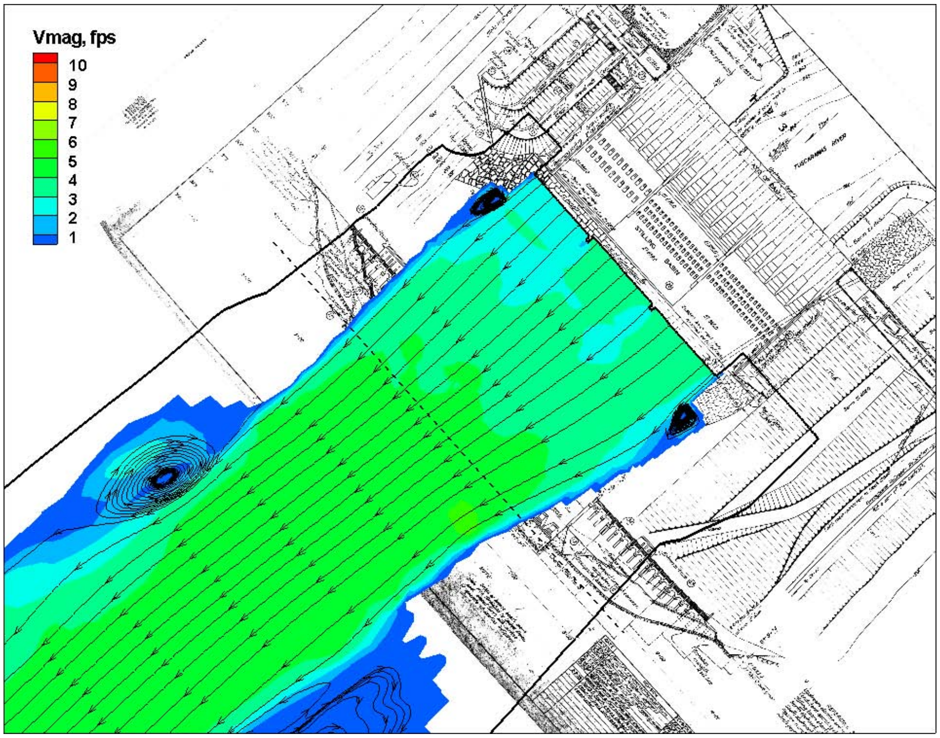

Figure 12. Velocity magnitude contours and stream traces downstream of Dover Dam, flow Condition 1, discharge 23,500 cfs, stilling basin tailwater el 881.2.

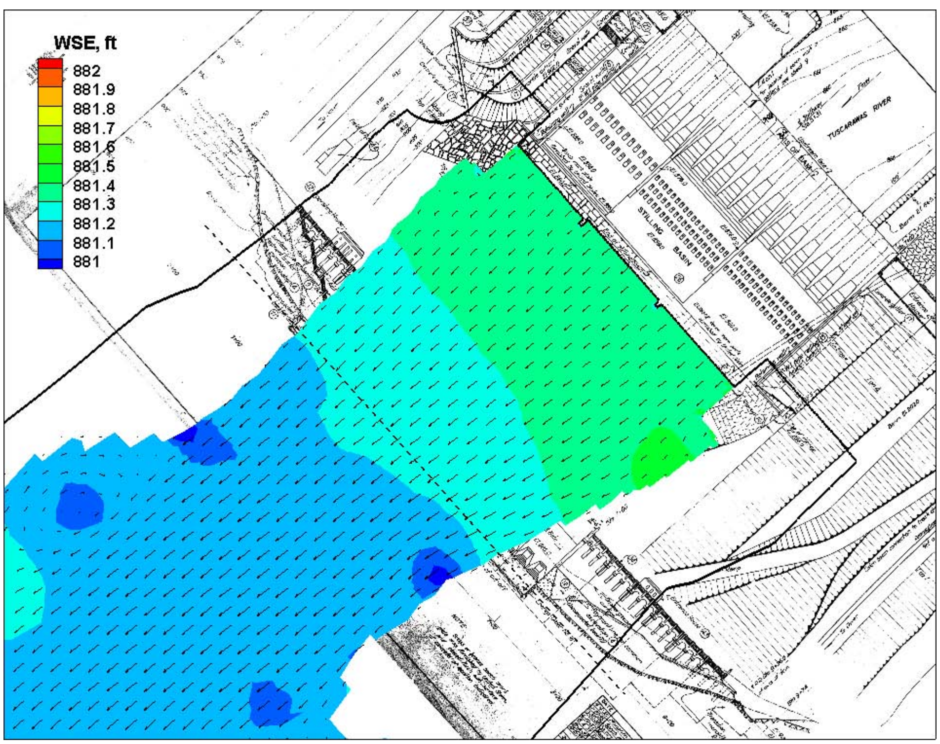

Figure 13. Water surface contours and vectors, flow Condition 1, discharge 23,500 cfs, stilling basin tailwater el 881.2.

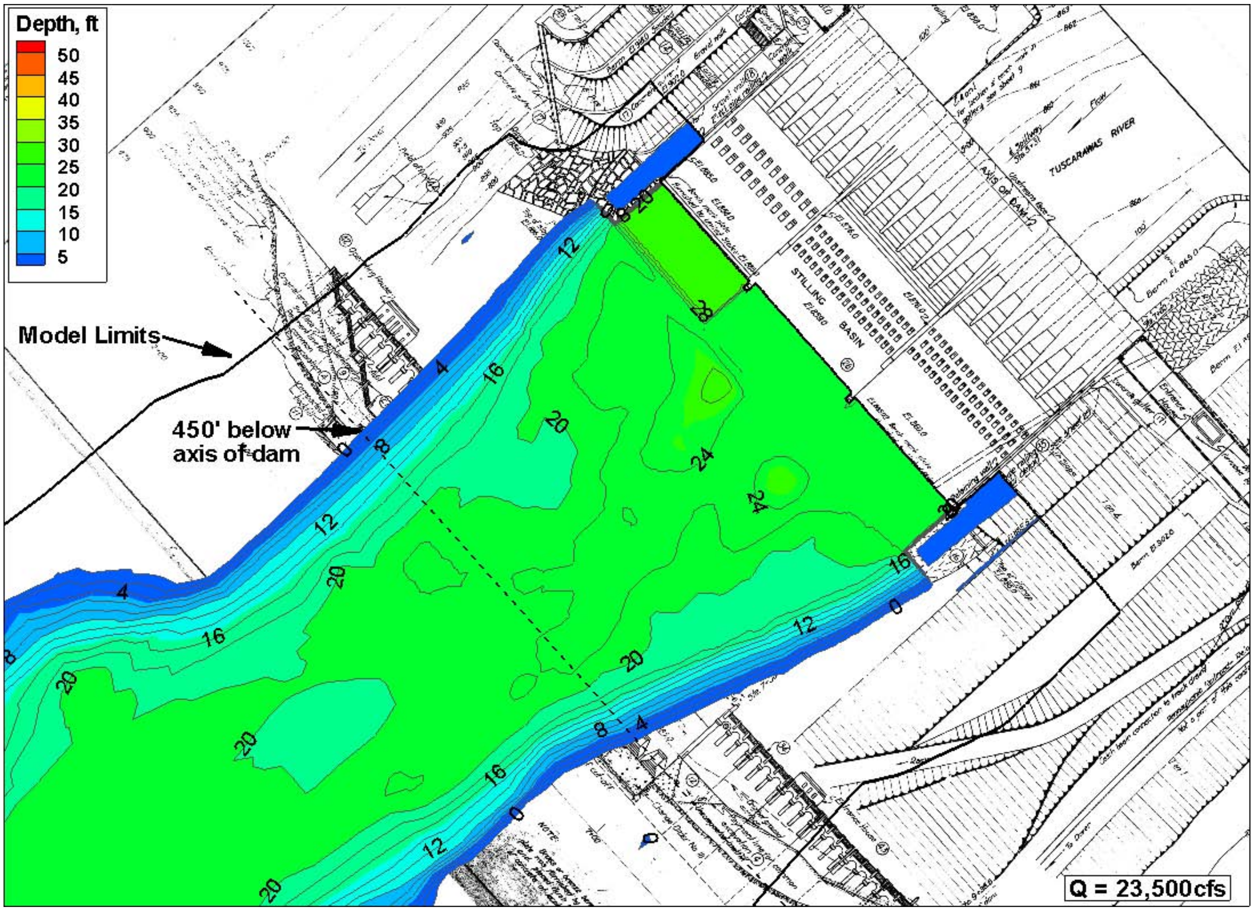

Figure 14. Water depth contours, flow Condition 1, discharge 23,500 cfs, stilling basin tailwater el 881.2.

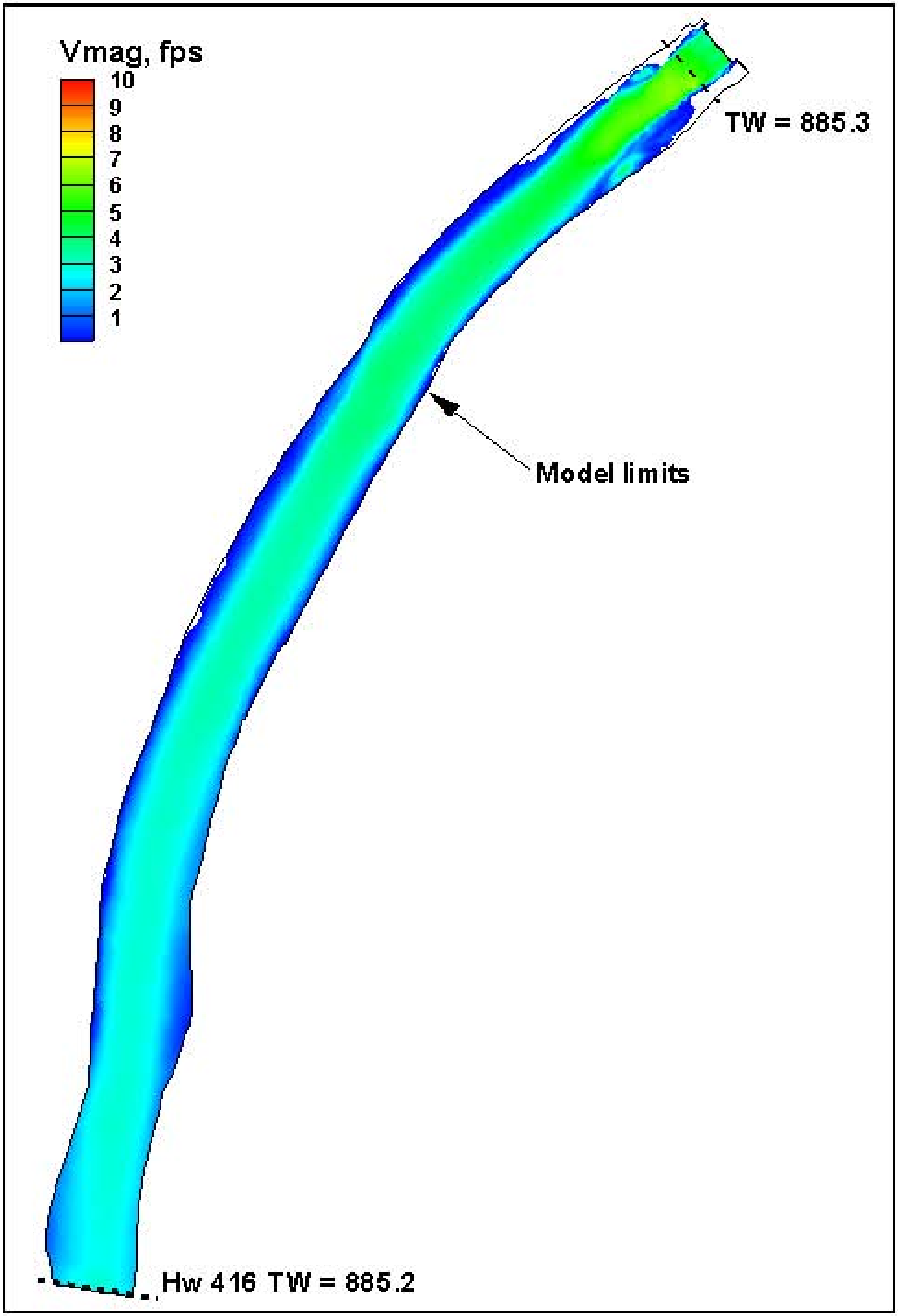

Figure 15. Velocity magnitude contours, flow Condition 2, discharge 38,000 cfs, stilling basin tailwater el 885.3.

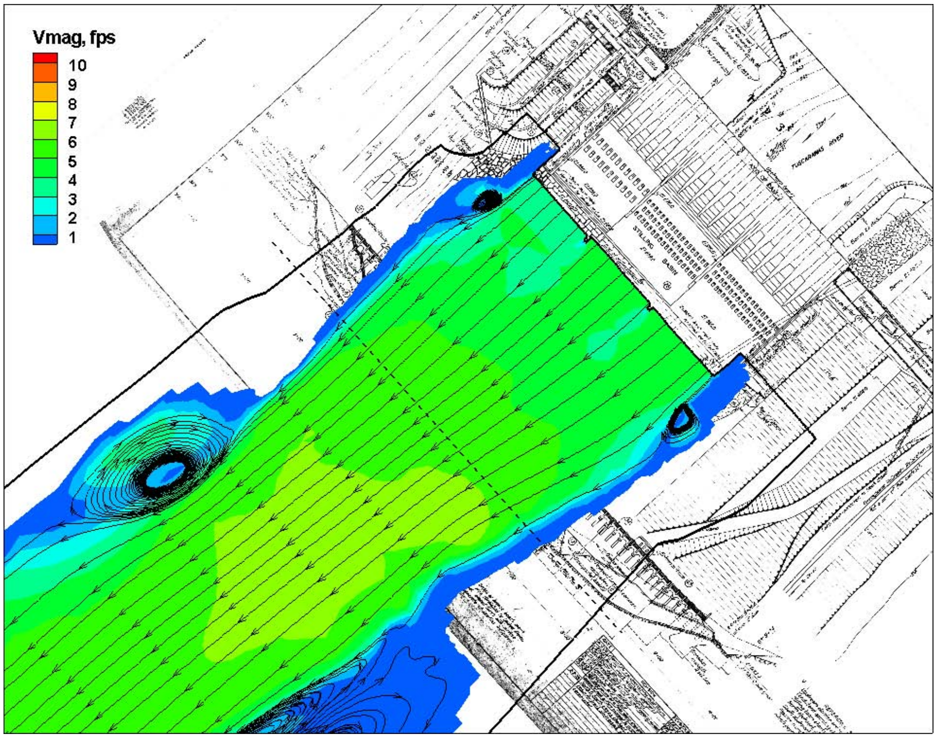

Figure 16. Velocity magnitude contours and stream traces downstream of Dover Dam, flow Condition 2, discharge 38,000 cfs, stilling basin tailwater el 885.3.

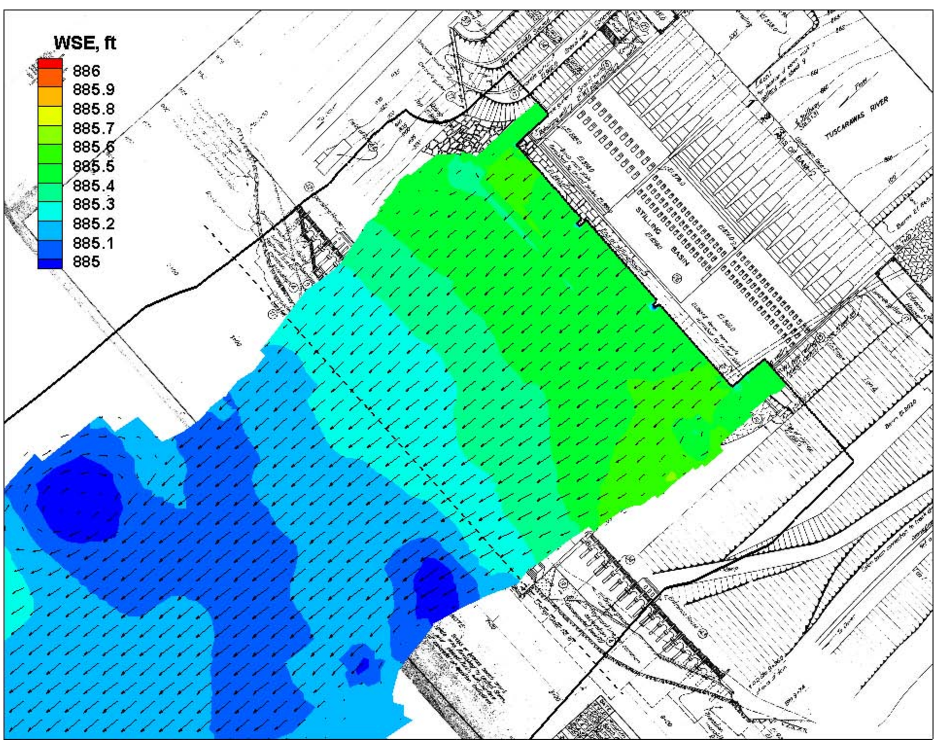

Figure 17. Water surface contours and vectors, flow Condition 2, discharge 38,000 cfs, stilling basin tailwater el 885.3.

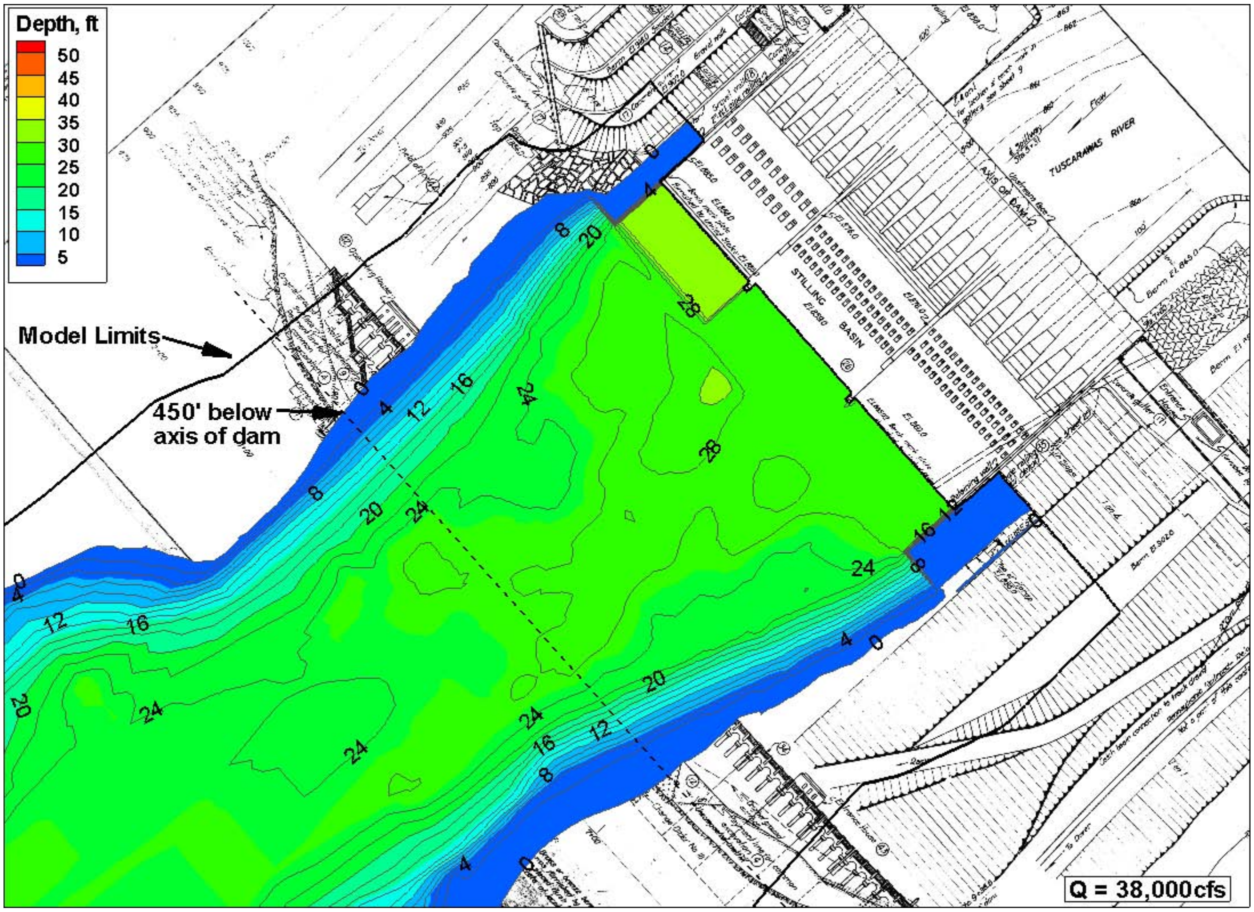

Figure 18. Water depth contours, flow Condition 2, discharge 38,000 cfs, stilling basin tailwater el 885.3.

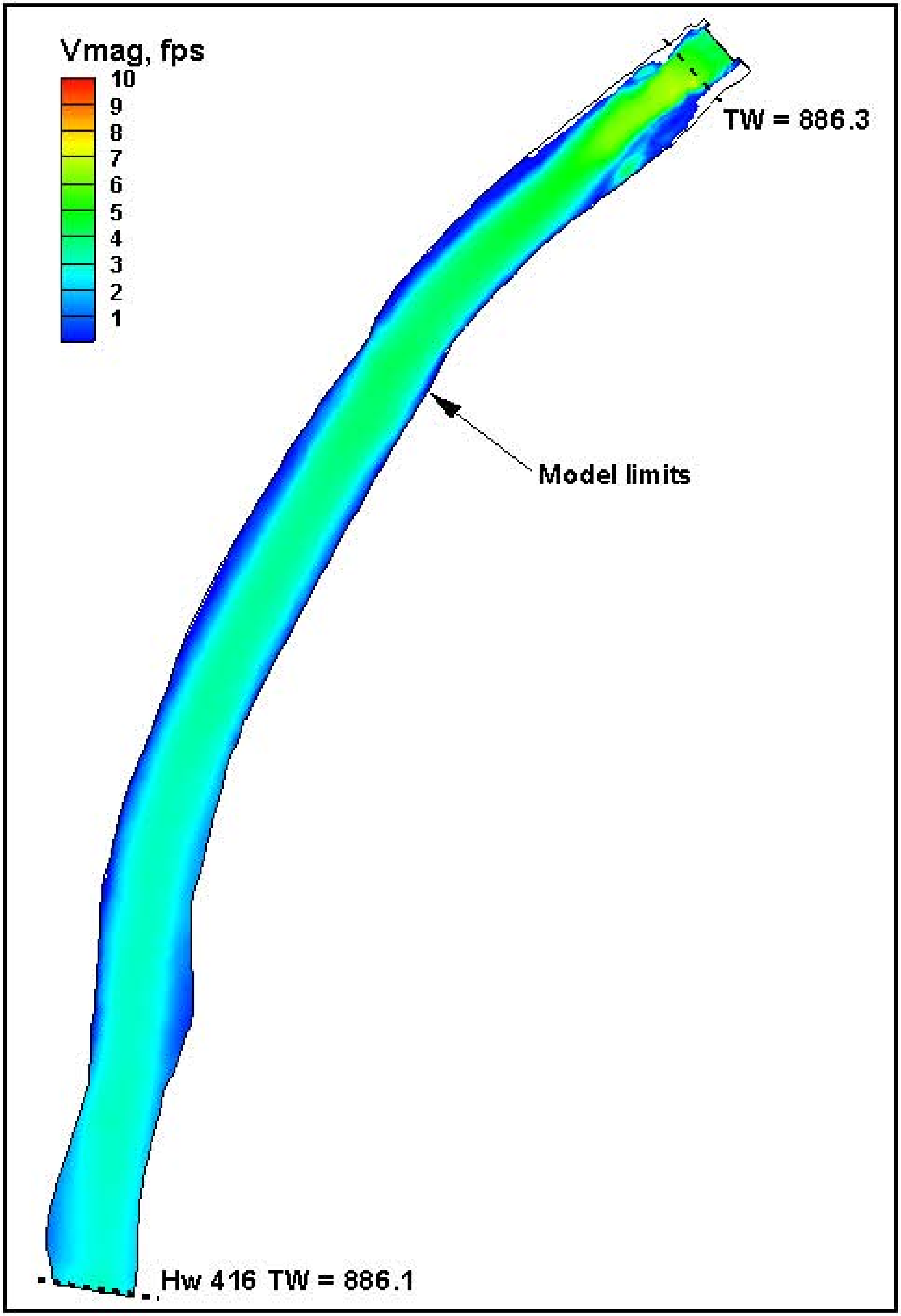

Figure 19. Velocity magnitude contours, flow Condition 3, discharge 42,000 cfs, stilling basin tailwater el 886.3.

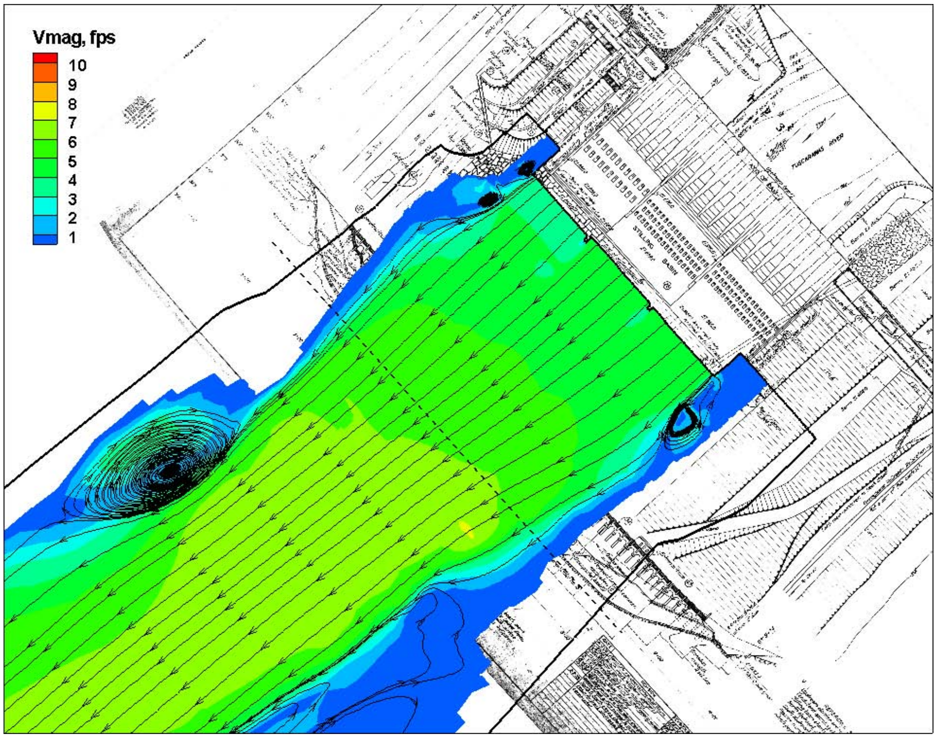

Figure 20. Velocity magnitude contours and stream traces downstream of Dover Dam, flow Condition 3, discharge 42,000 cfs, stilling basin tailwater el 886.3.

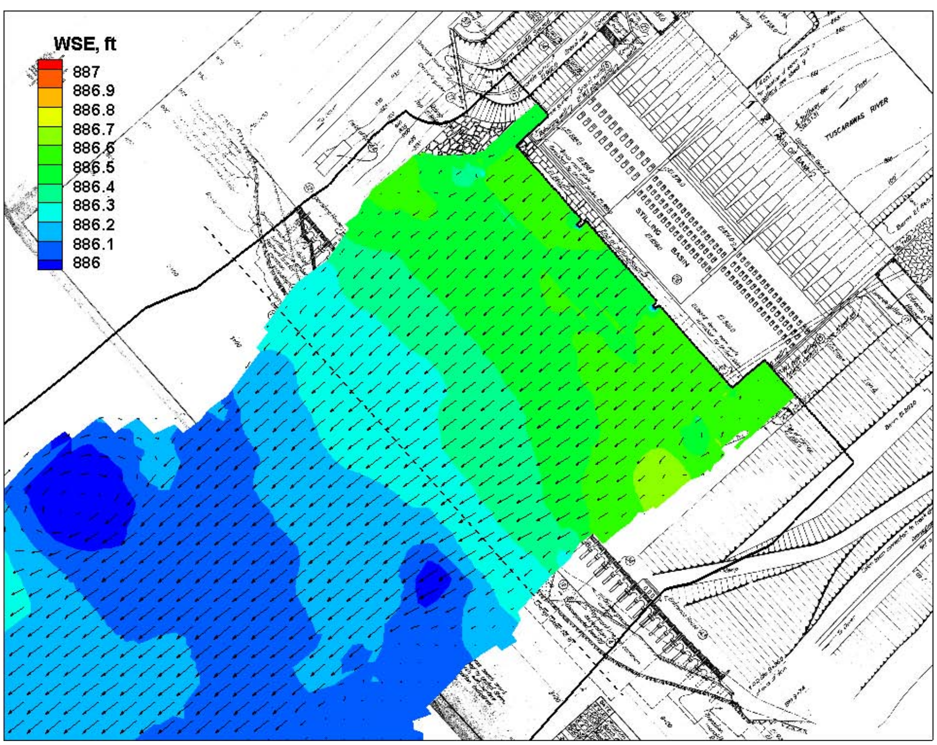

Figure 21. Water surface contours and vectors, flow Condition 3, discharge 42,000 cfs, stilling basin tailwater el 886.3.

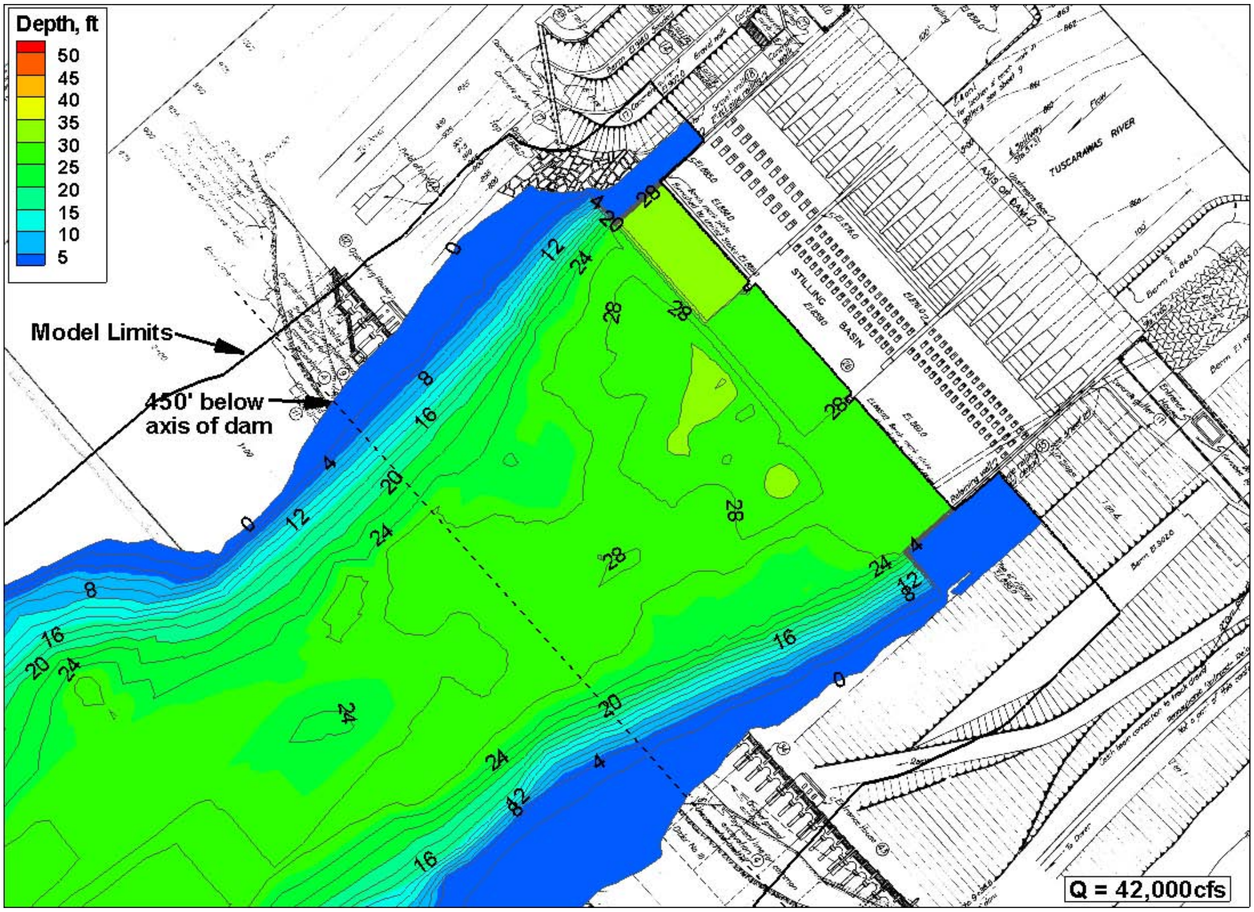

Figure 22. Water depth contours, flow Condition 3, discharge 42,000 cfs, stilling basin tailwater el 886.3.

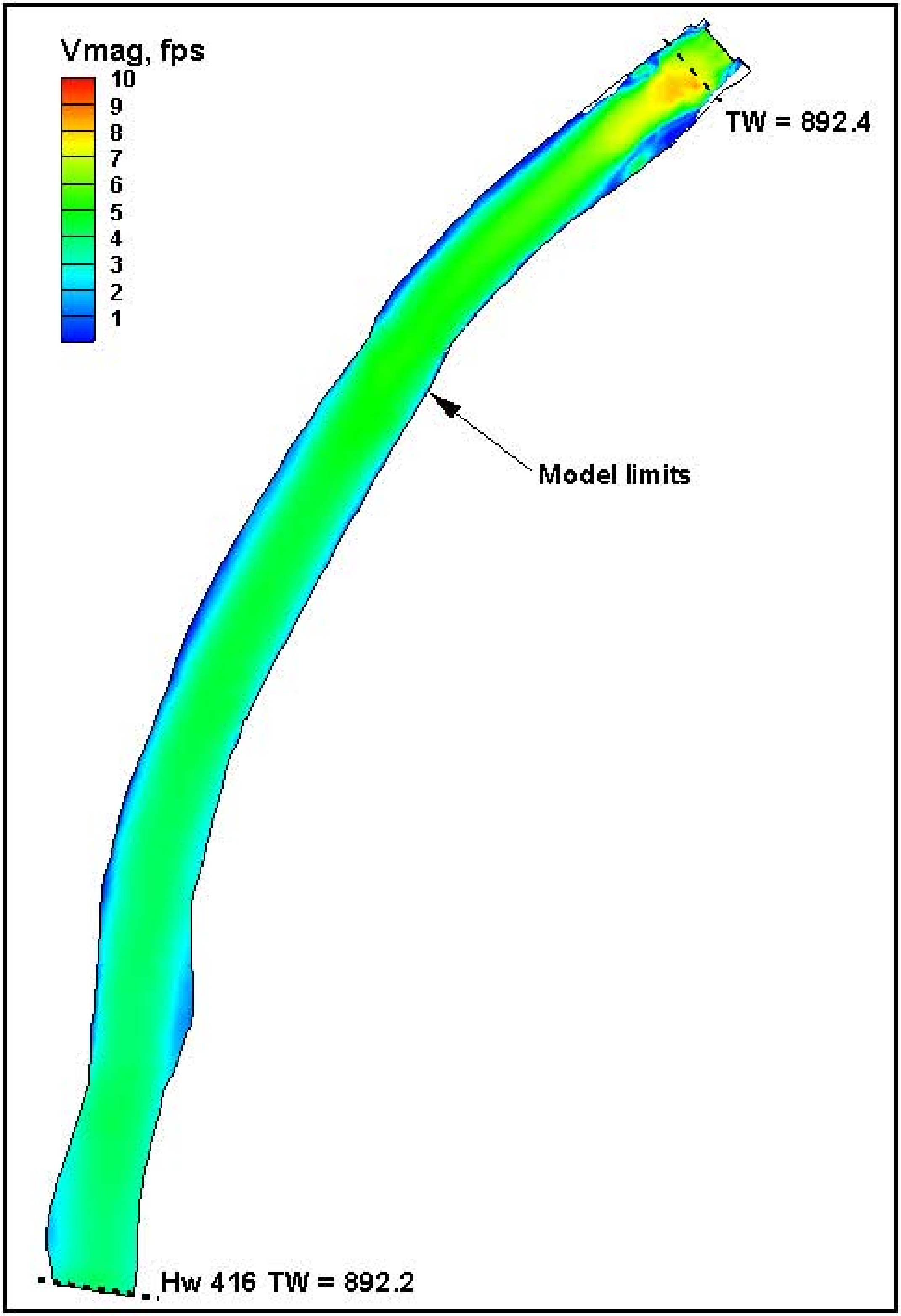

Figure 23. Velocity magnitude contours, flow Condition 4, discharge 72,500 cfs, stilling basin tailwater el 892.4.

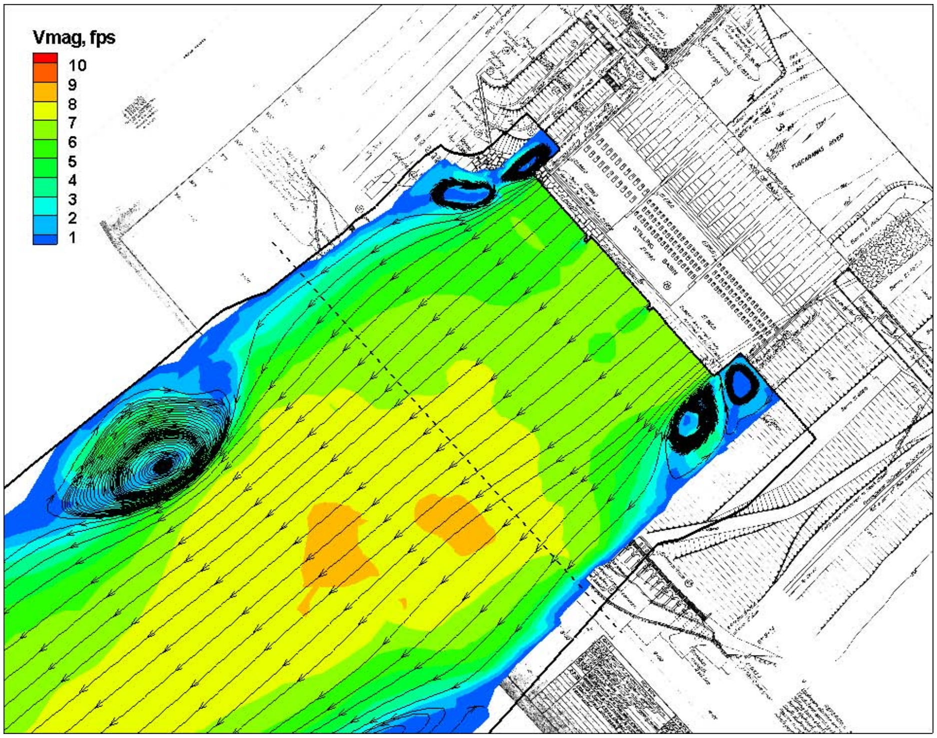

Figure 24. Velocity magnitude contours and stream traces downstream of Dover Dam, flow Condition 4, discharge 72,500 cfs, stilling basin tailwater el 892.4.

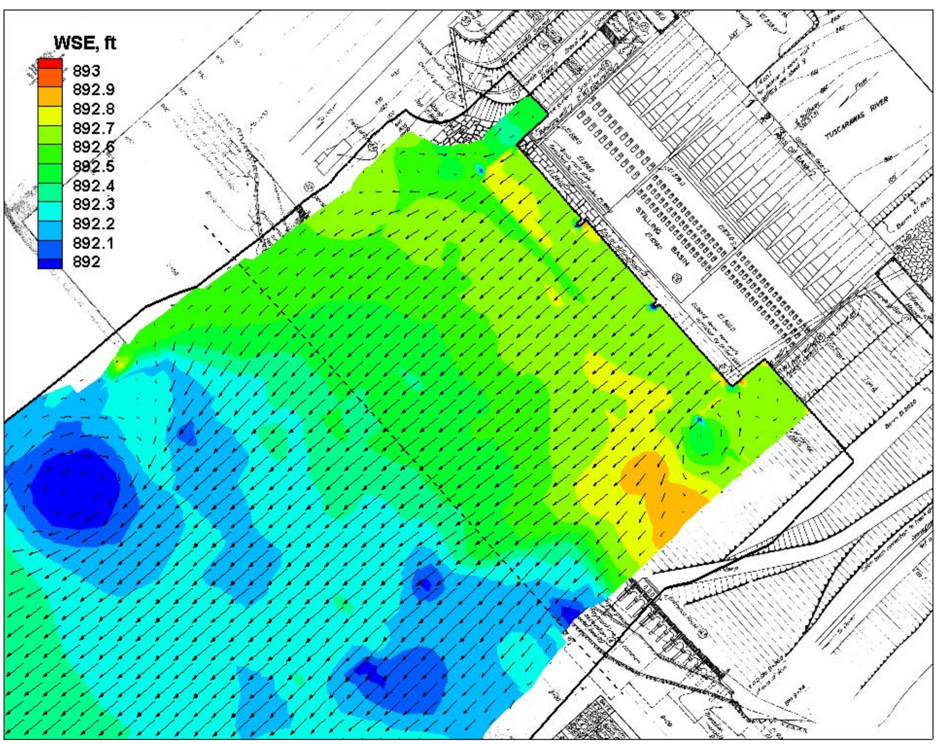

Figure 25. Water surface contours and vectors, flow Condition 4, discharge 72,500 cfs, stilling basin tailwater el 892.4.

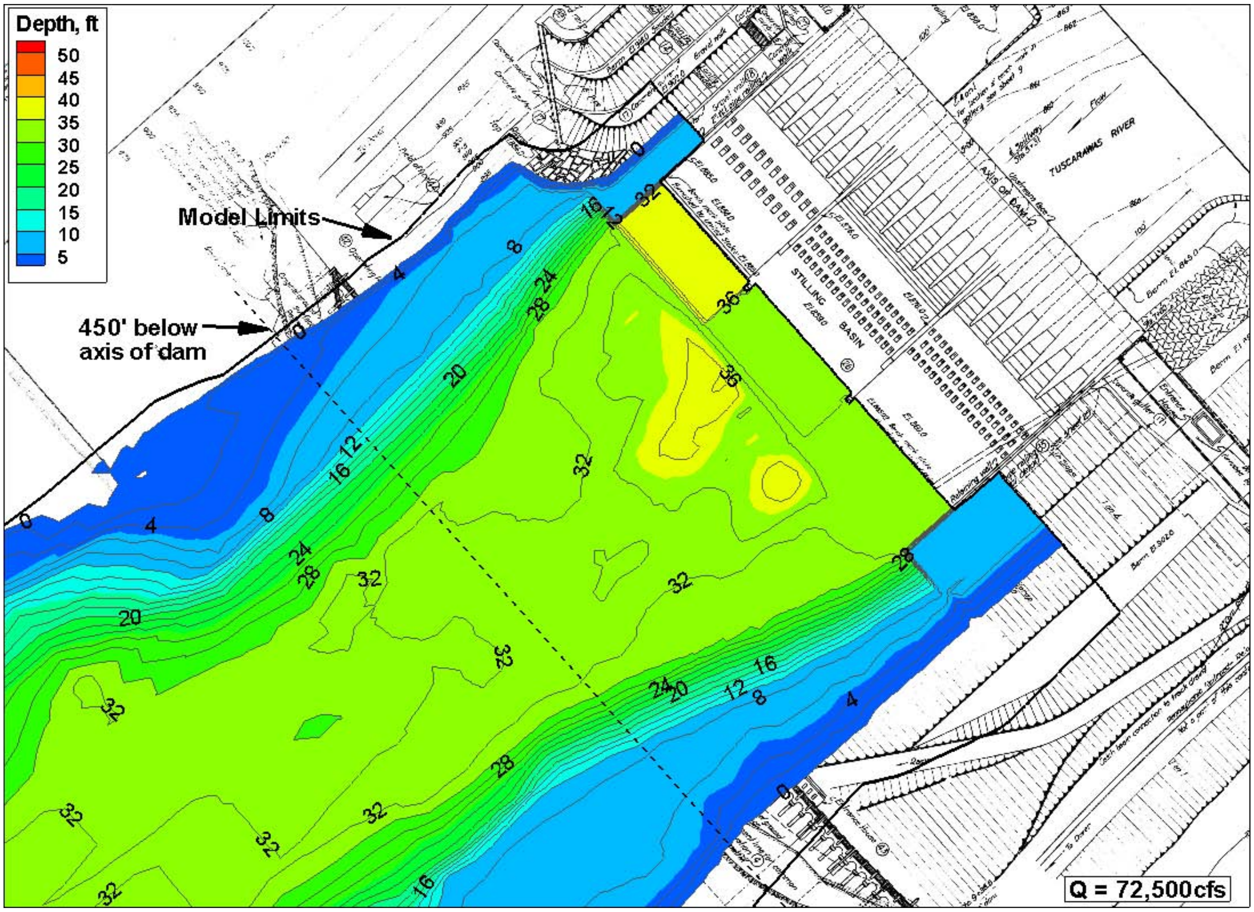

Figure 26. Water depth contours, flow Condition 4, discharge 72,500 cfs, stilling basin tailwater el 892.4.

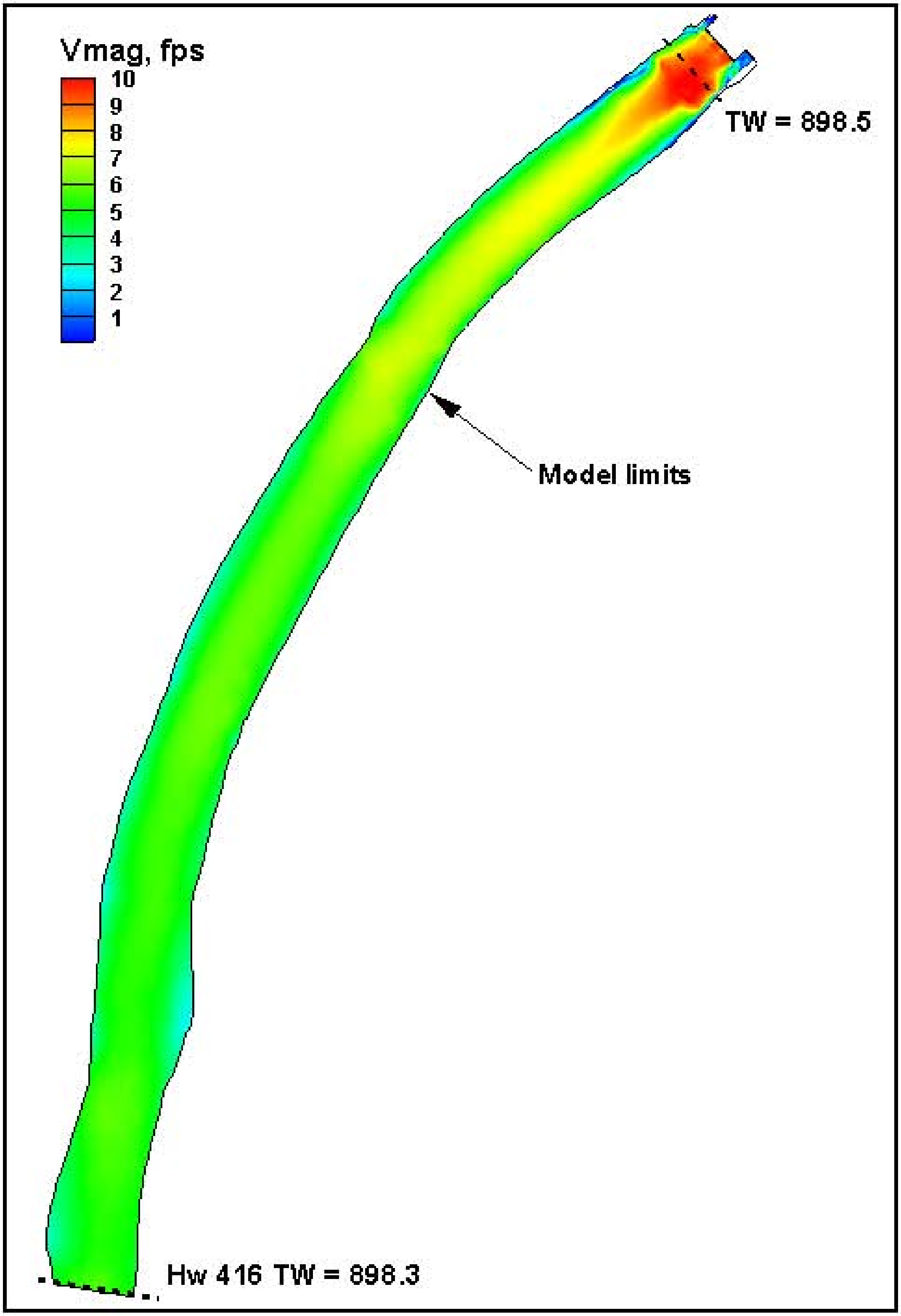

Figure 27. Velocity magnitude contours, flow Condition 5, discharge 125,000 cfs, stilling basin tailwater el 898.5.

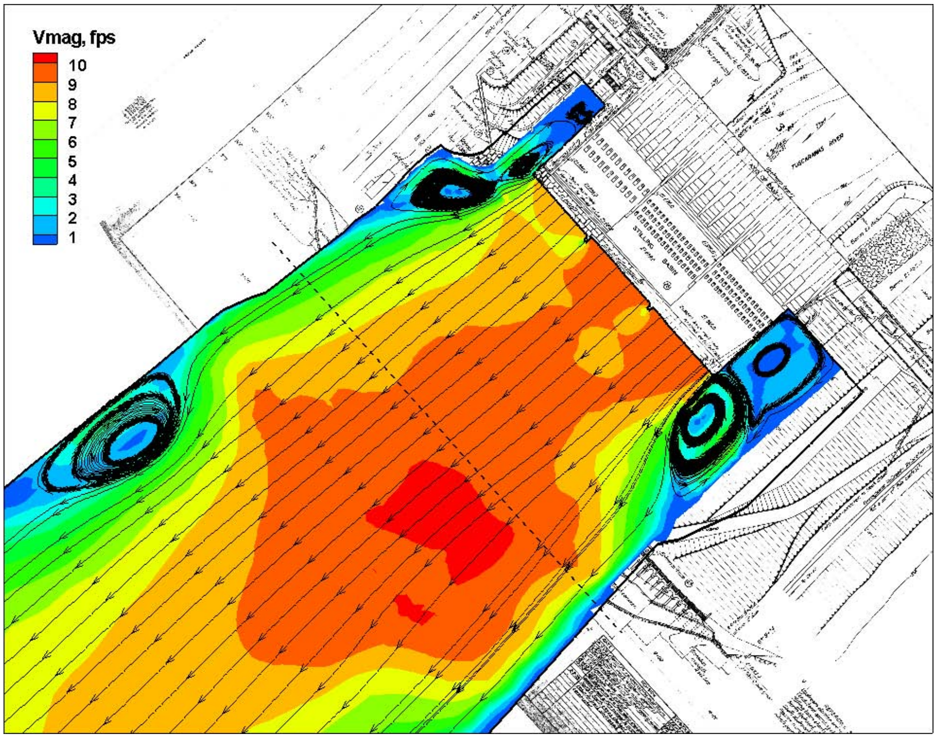

Figure 28. Velocity magnitude contours and stream traces downstream of Dover Dam, flow Condition 5, discharge 125,000 cfs, stilling basin tailwater el 898.5.

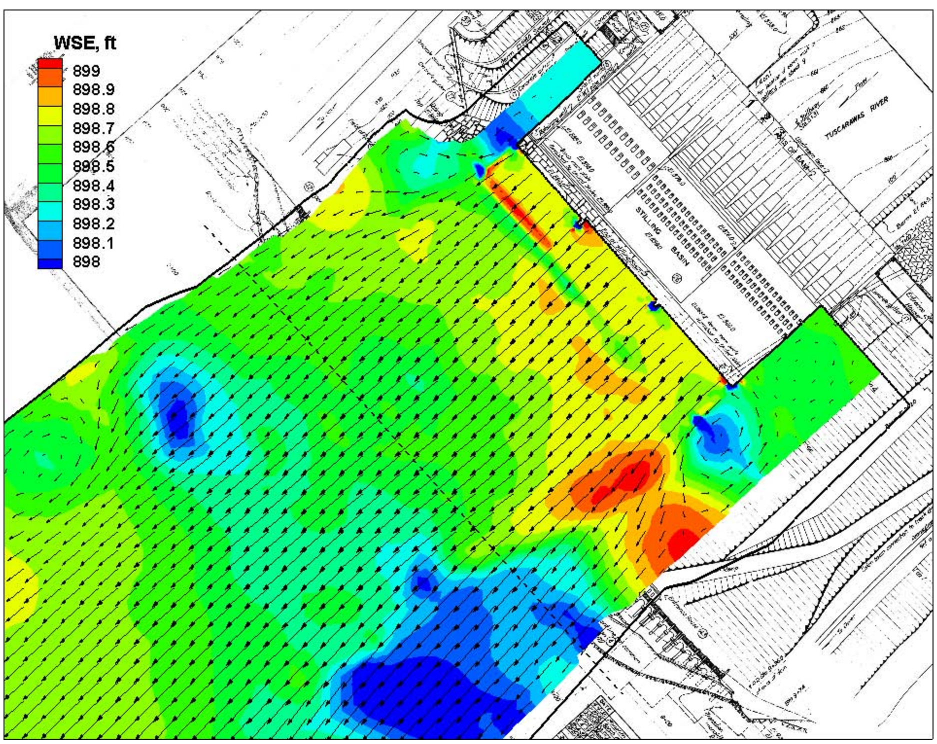

Figure 29. Water surface contours and vectors, flow Condition 5, discharge 125,000 cfs, stilling basin tailwater el 898.5.

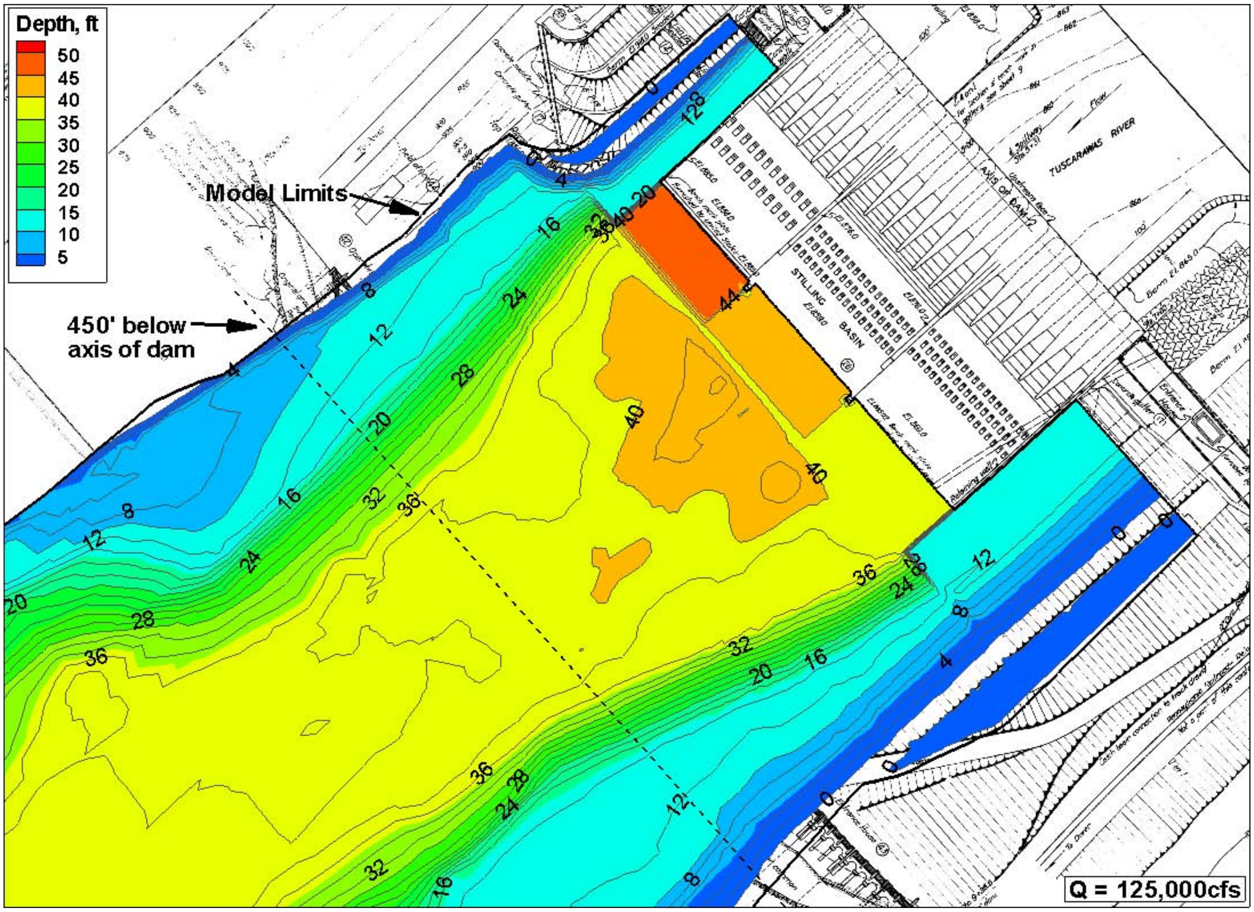

Figure 30. Water depth contours, flow Condition 5, discharge 125,000 cfs, stilling basin tailwater el 898.5.

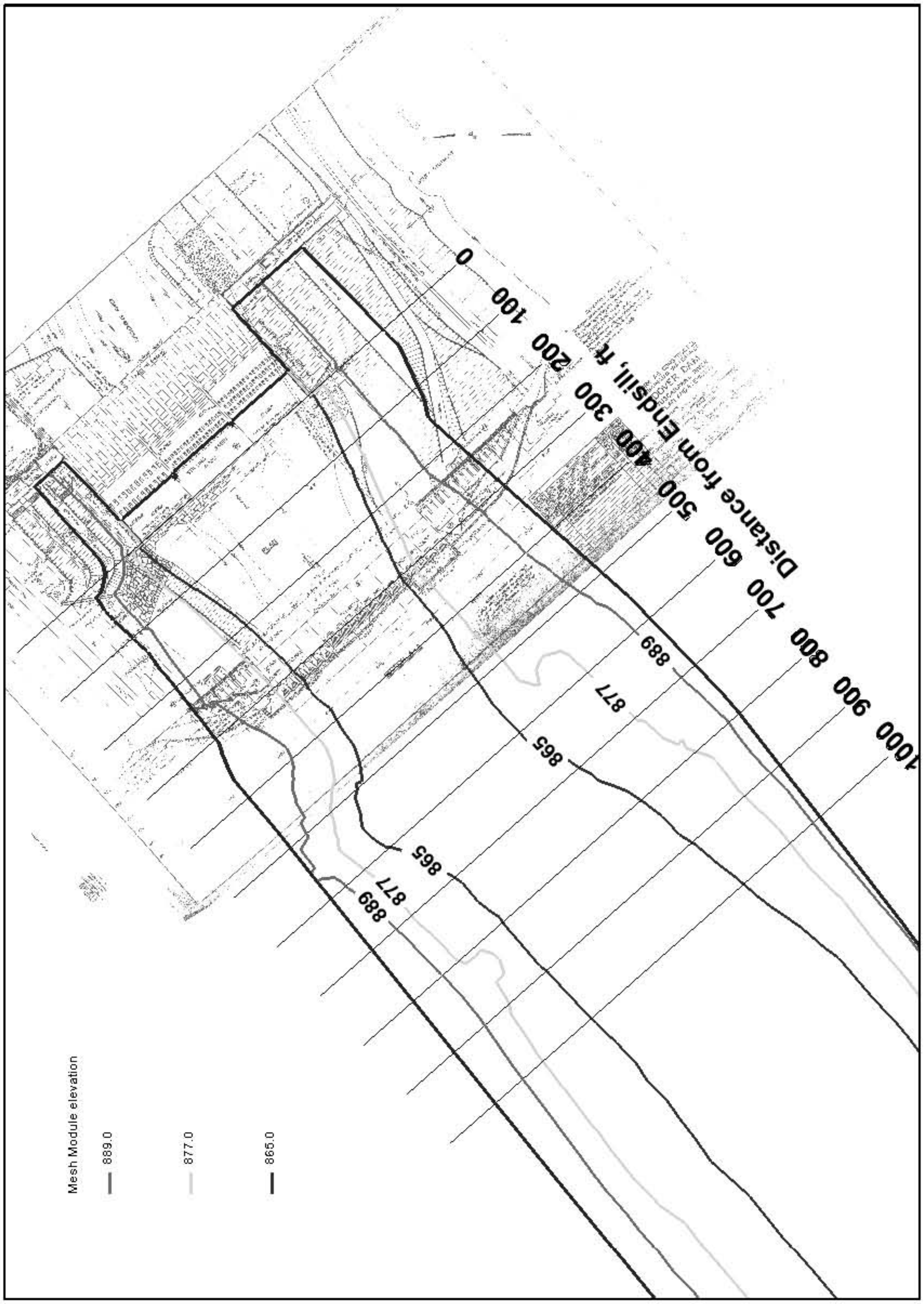

Figure 31. Contour lines at el 865, el 877, and el 889.

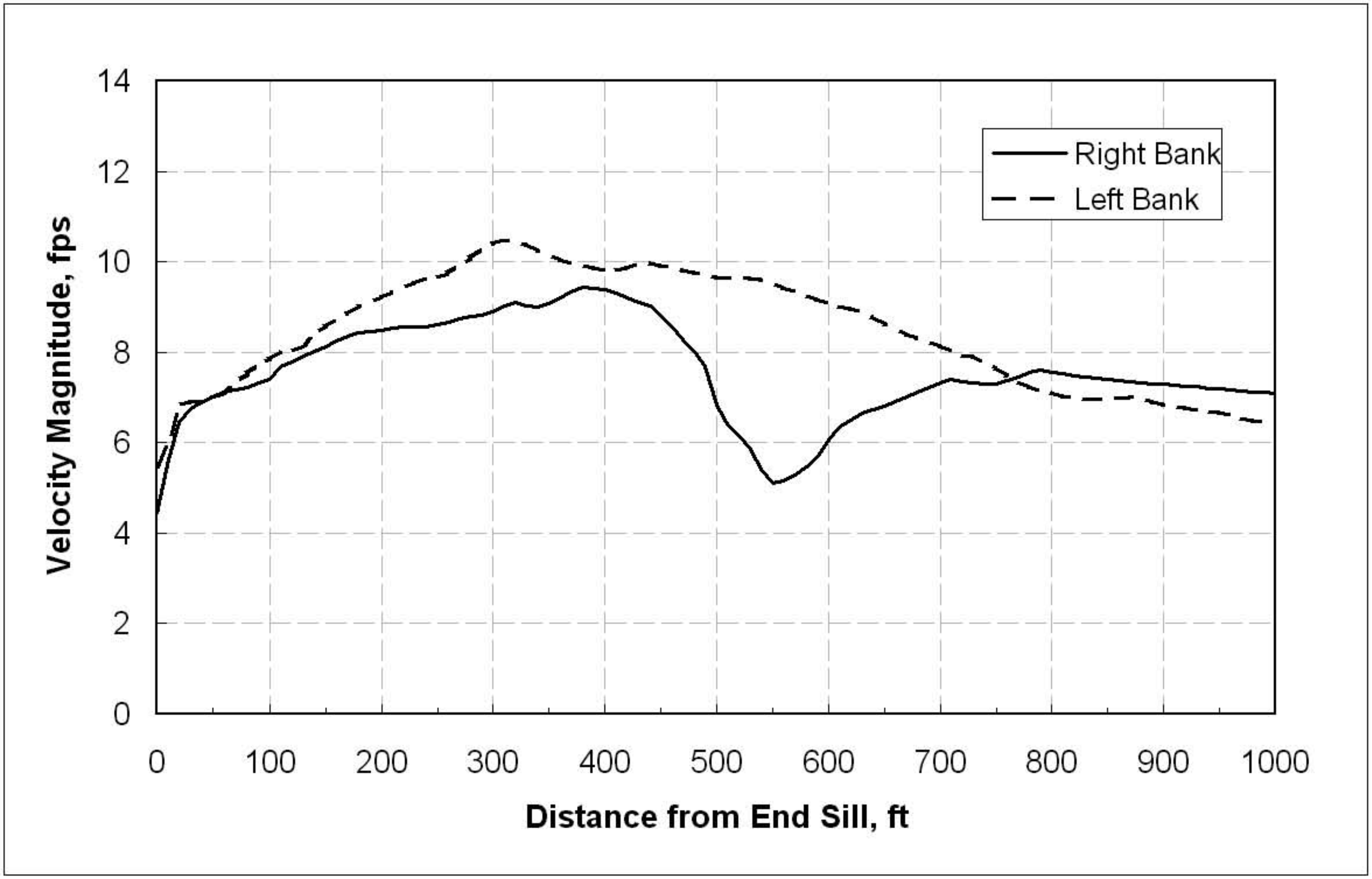

Figure 32. Velocity magnitude profile at el 865, Condition 5, discharge 125,000 cfs, stilling basin tailwater el 898.5 (left and right are referenced to looking downstream).

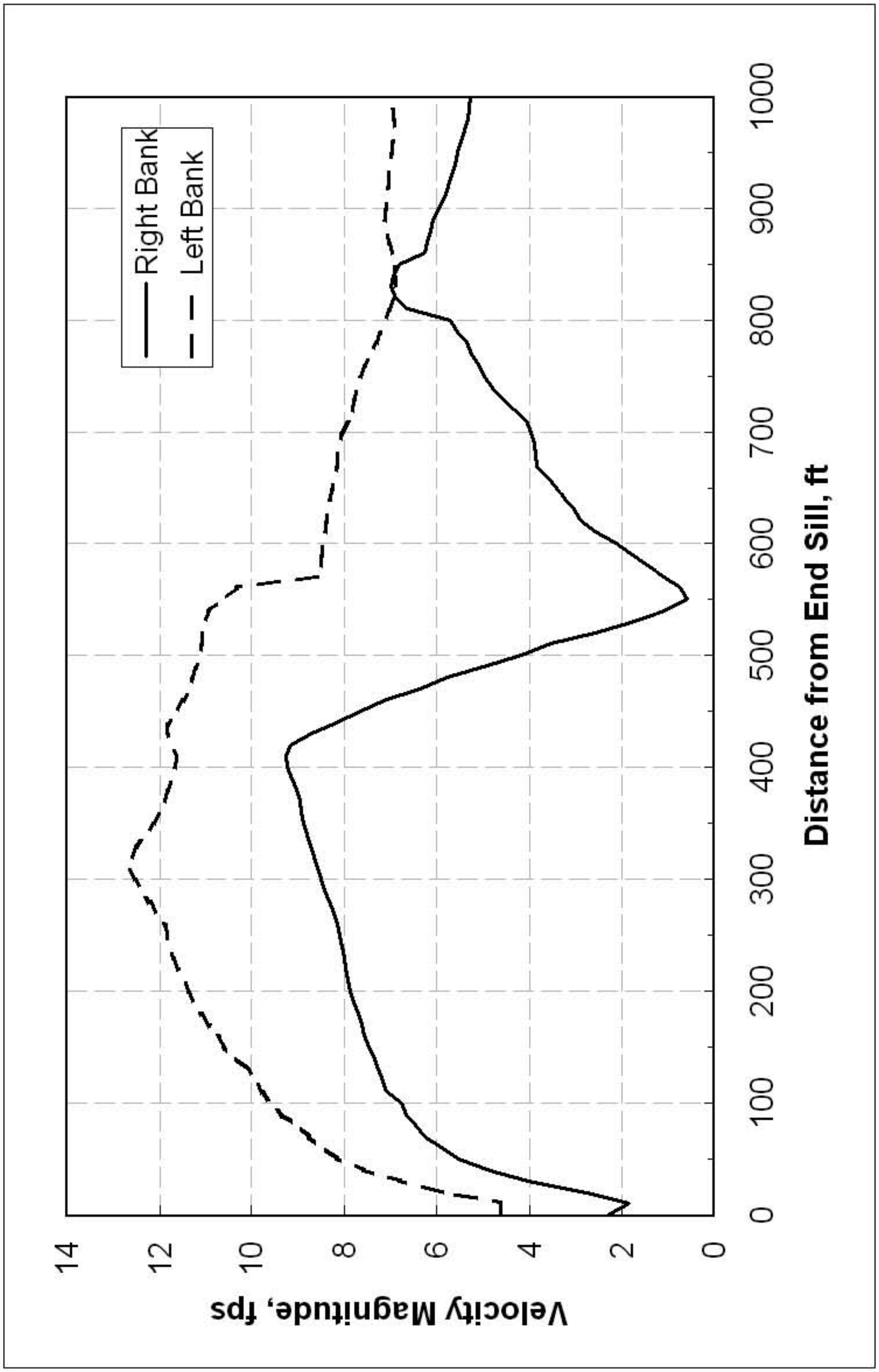

Figure 33. Velocity magnitude profile at el 877, Condition 5, discharge 125,000 cfs, stilling basin tailwater el 898.5 (left and right are referenced to looking downstream).

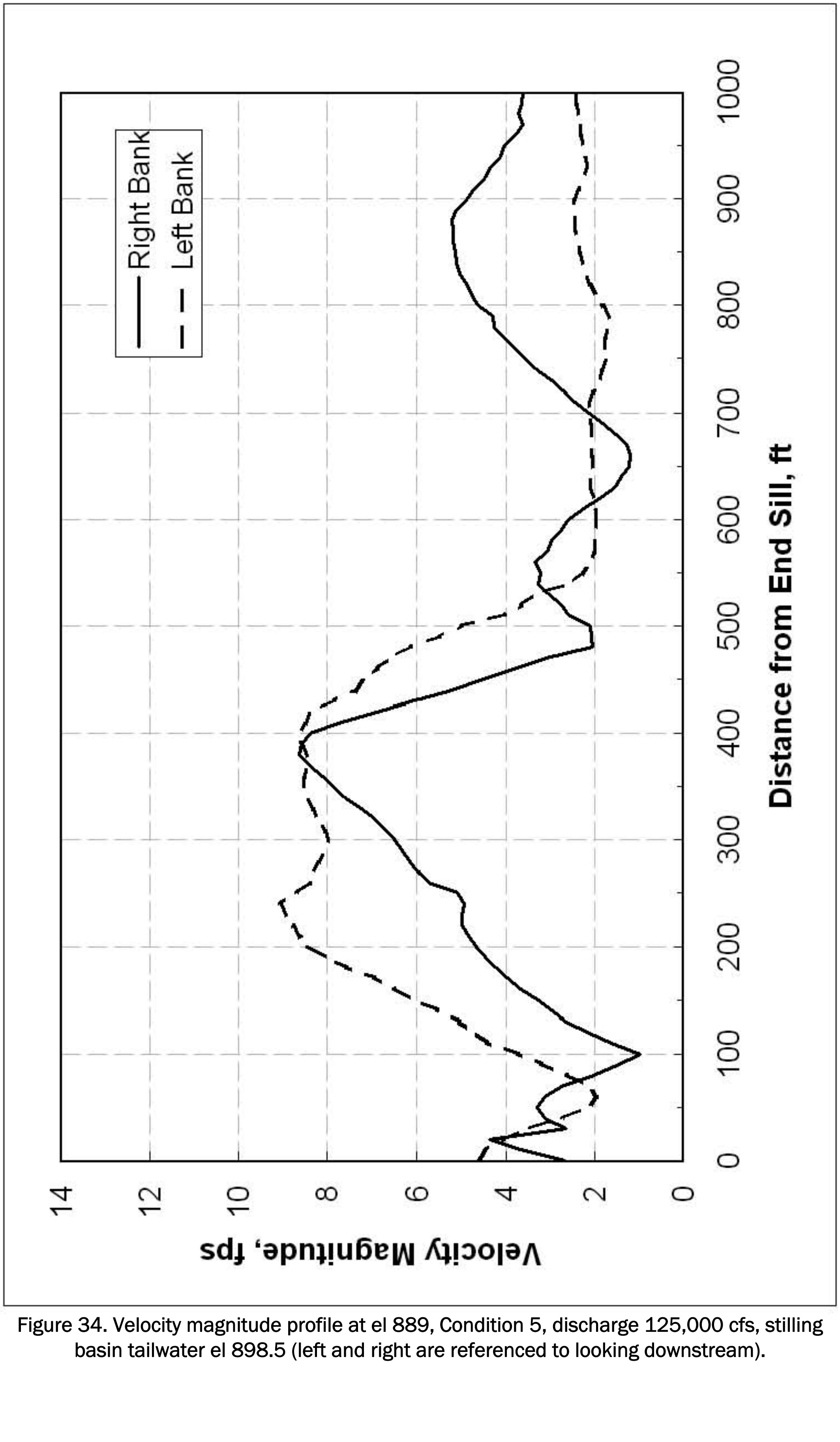

Figure 34. Velocity magnitude profile at el 889, Condition 5, discharge 125,000 cfs, stilling basin tailwater el 898.5 (left and right are referenced to looking downstream).

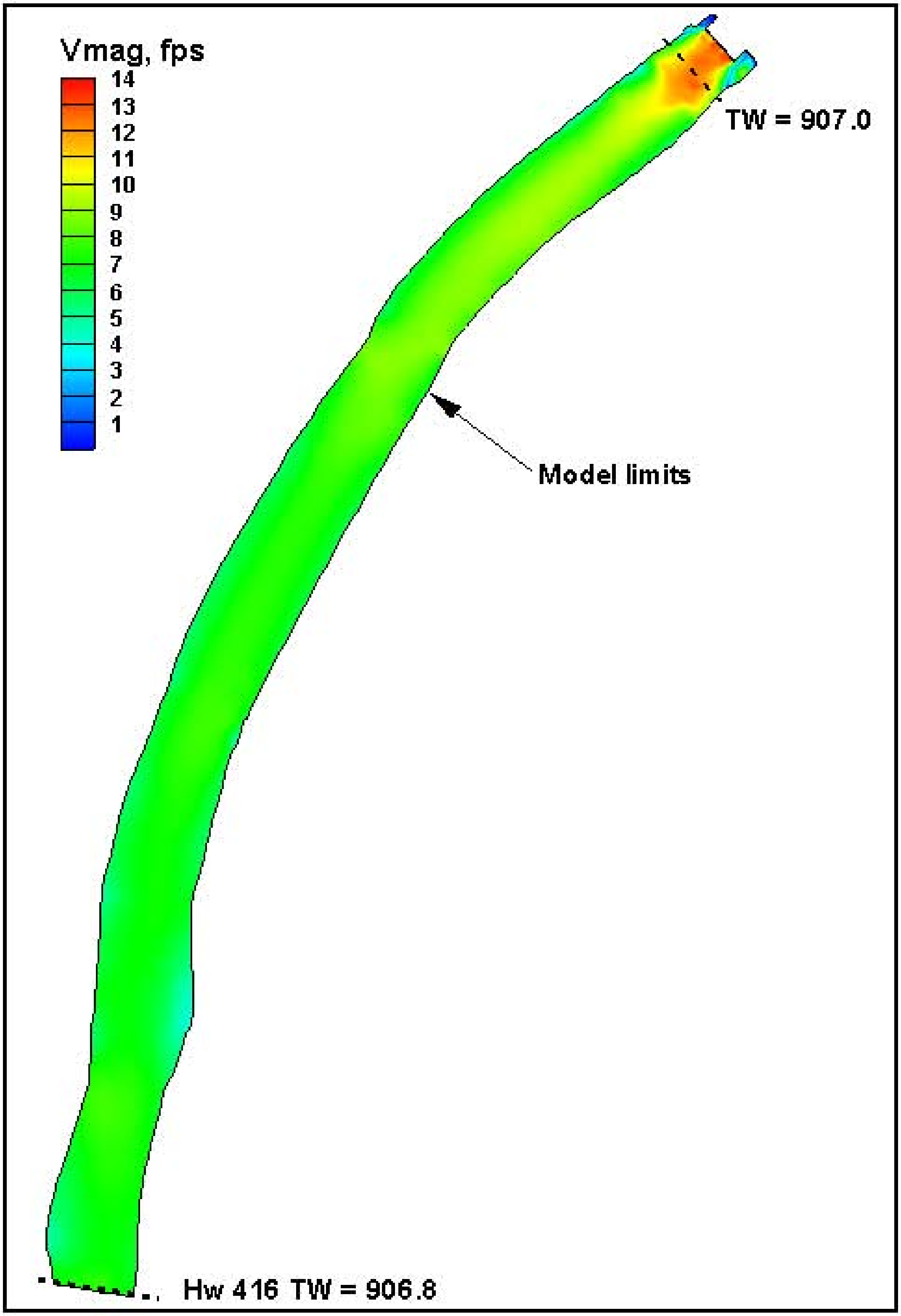

Figure 35. Velocity magnitude contours, flow Condition 6 (PMF), discharge 207,000 cfs, stilling basin tailwater el 907.0.

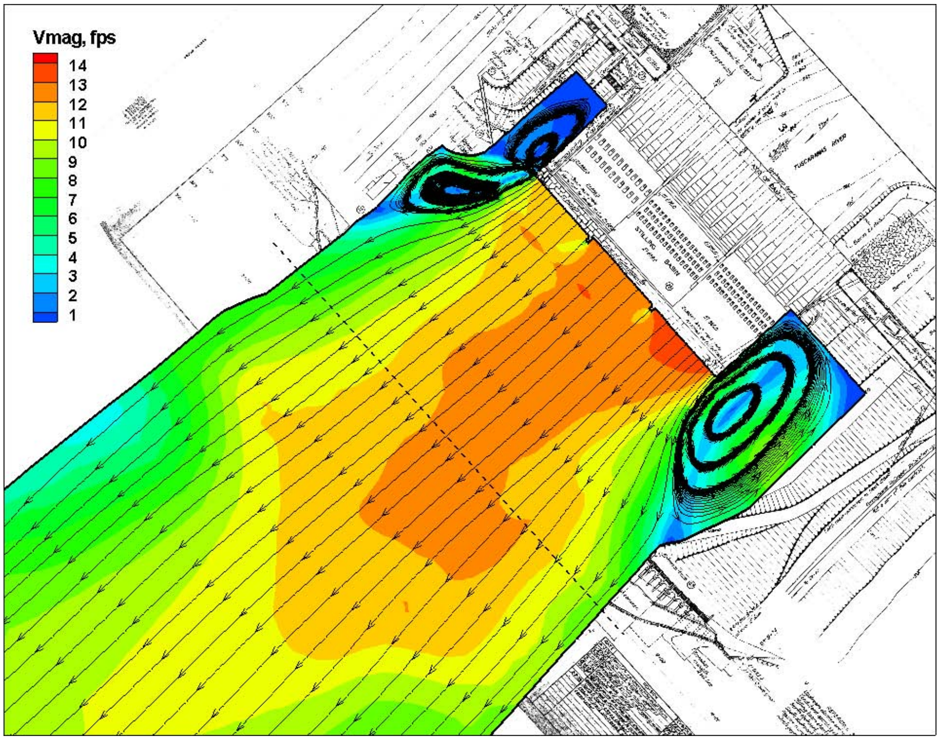

Figure 36. Velocity magnitude contours and stream traces downstream of Dover Dam, flow Condition 6 (PMF), discharge 207,000 cfs, stilling basin tailwater el 907.0.

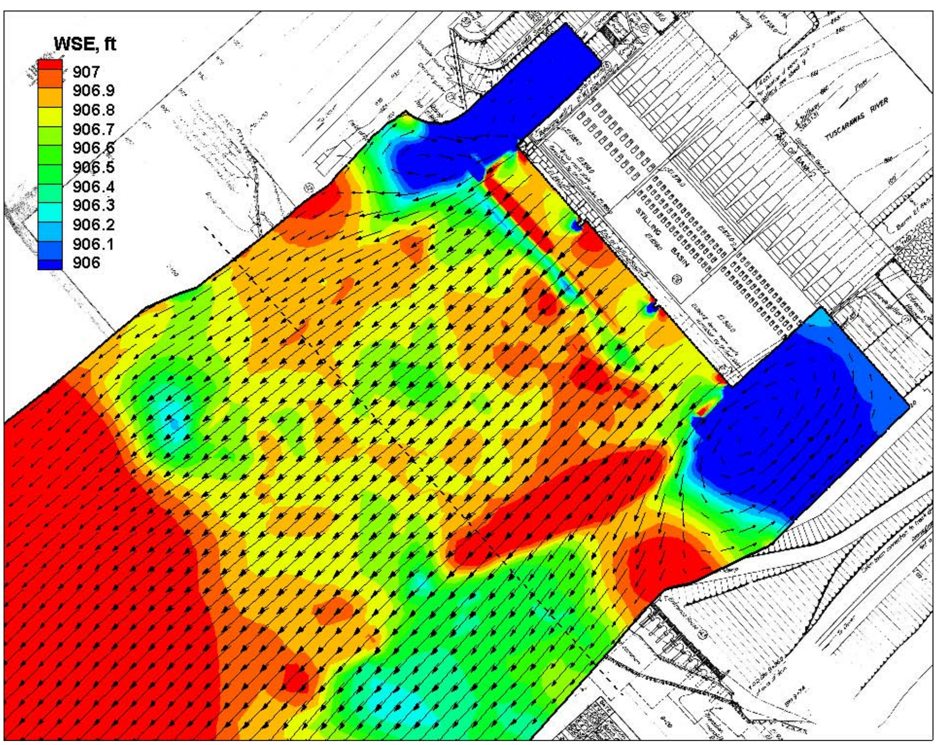

Figure 37. Water surface contours and vectors, flow Condition 6 (PMF), discharge 207,000 cfs, stilling basin tailwater el 907.0.

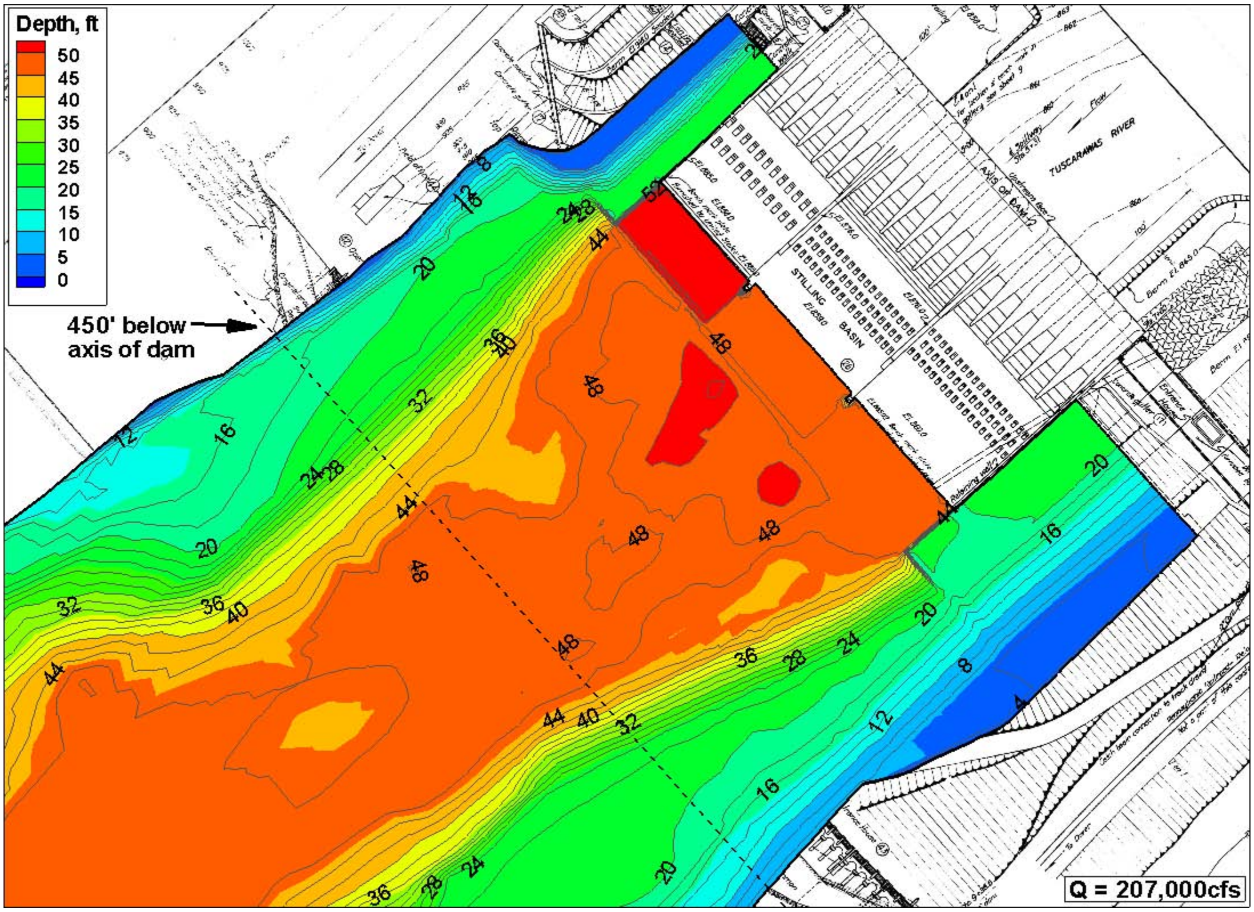

Figure 38. Water depth contours, flow Condition 6 (PMF), discharge 207,000 cfs, stilling basin tailwater el 907.0.

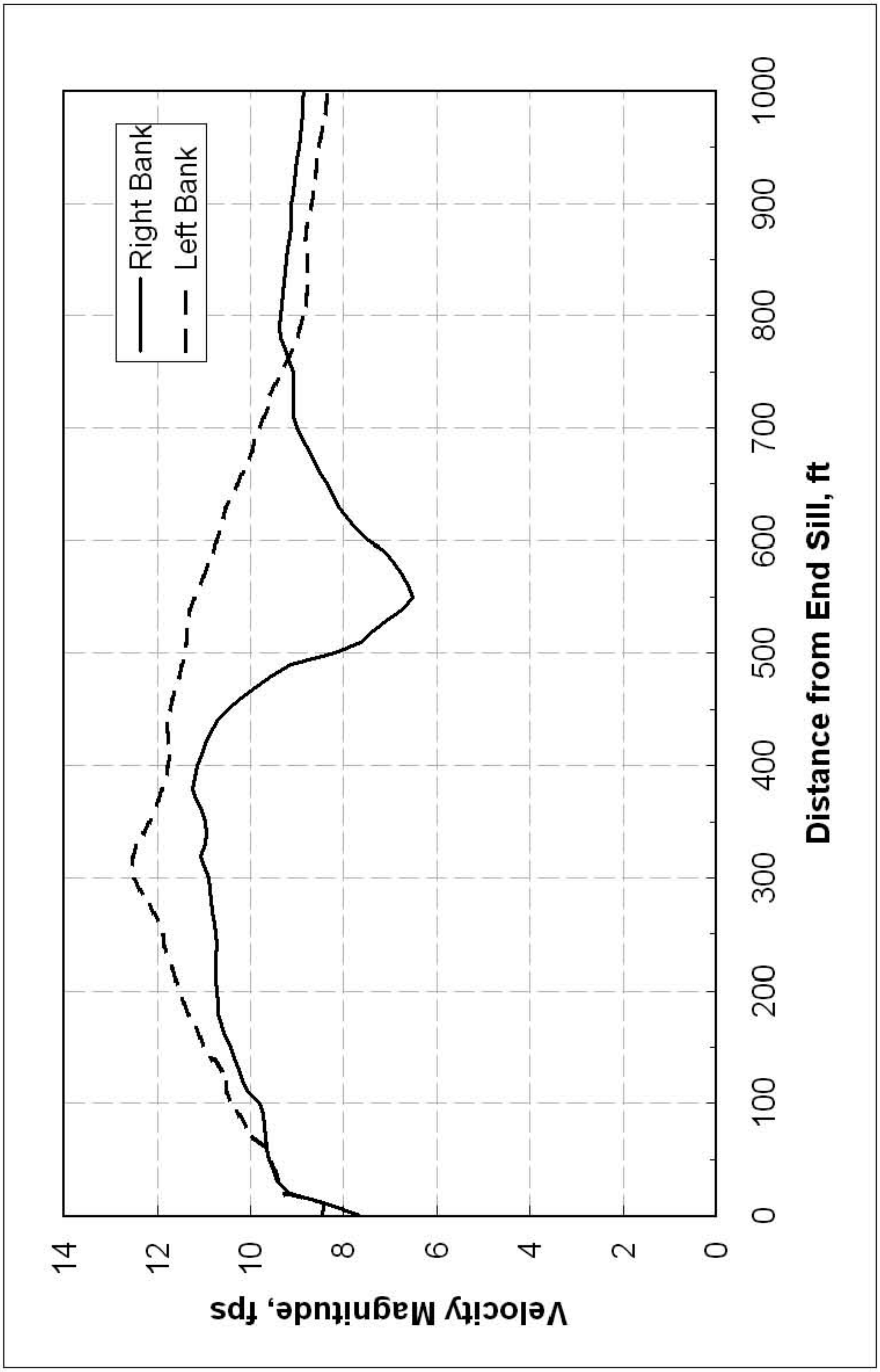

Figure 39. Velocity magnitude profile at el 865, Condition 6, discharge 207,000 cfs, stilling basin tailwater el 907.0 (left and right are referenced to looking downstream).

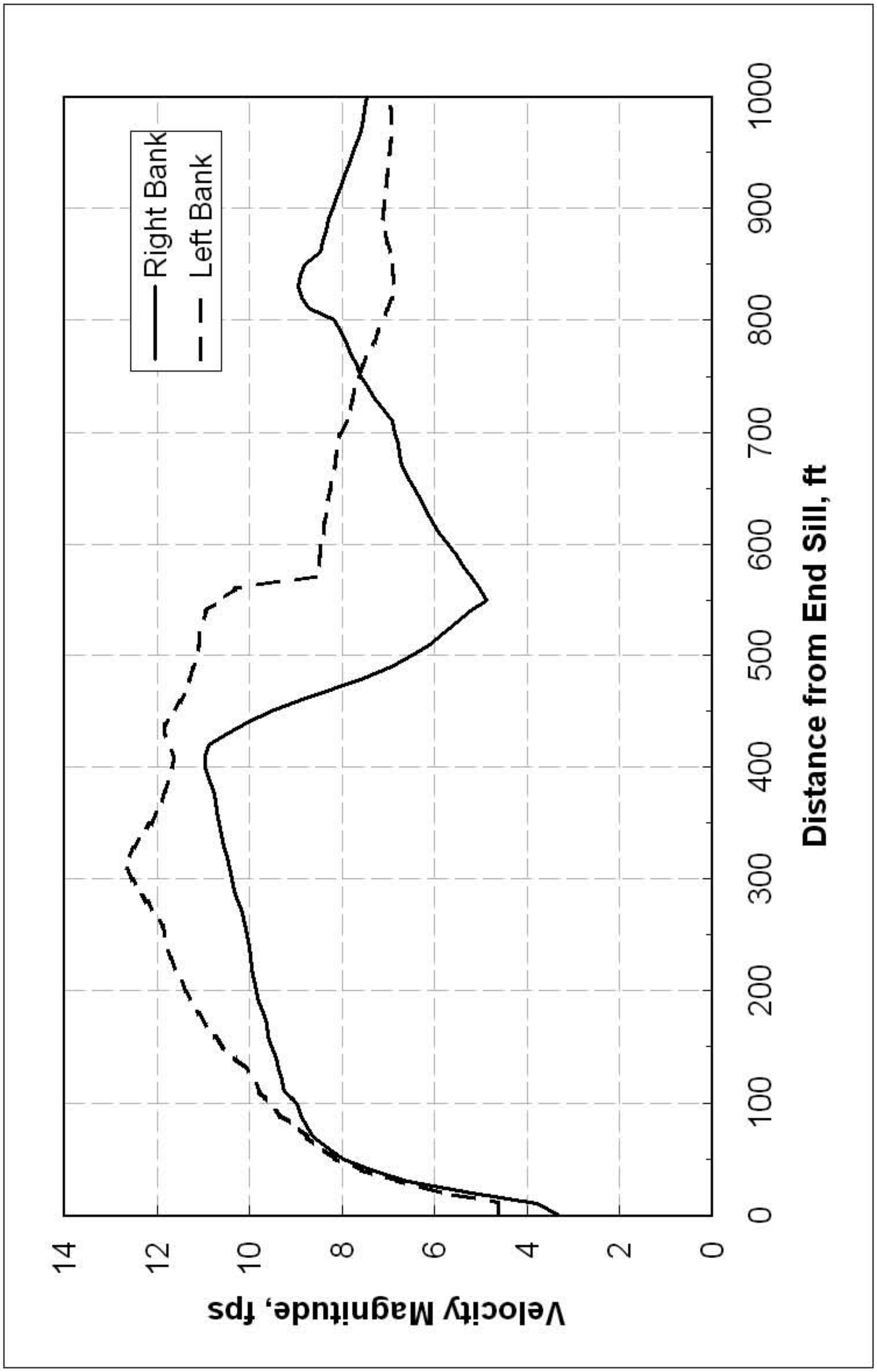

Figure 40. Velocity magnitude profile at el 877, Condition 6, discharge 207,000 cfs, stilling basin tailwater el 907.0 (left and right are referenced to looking downstream).

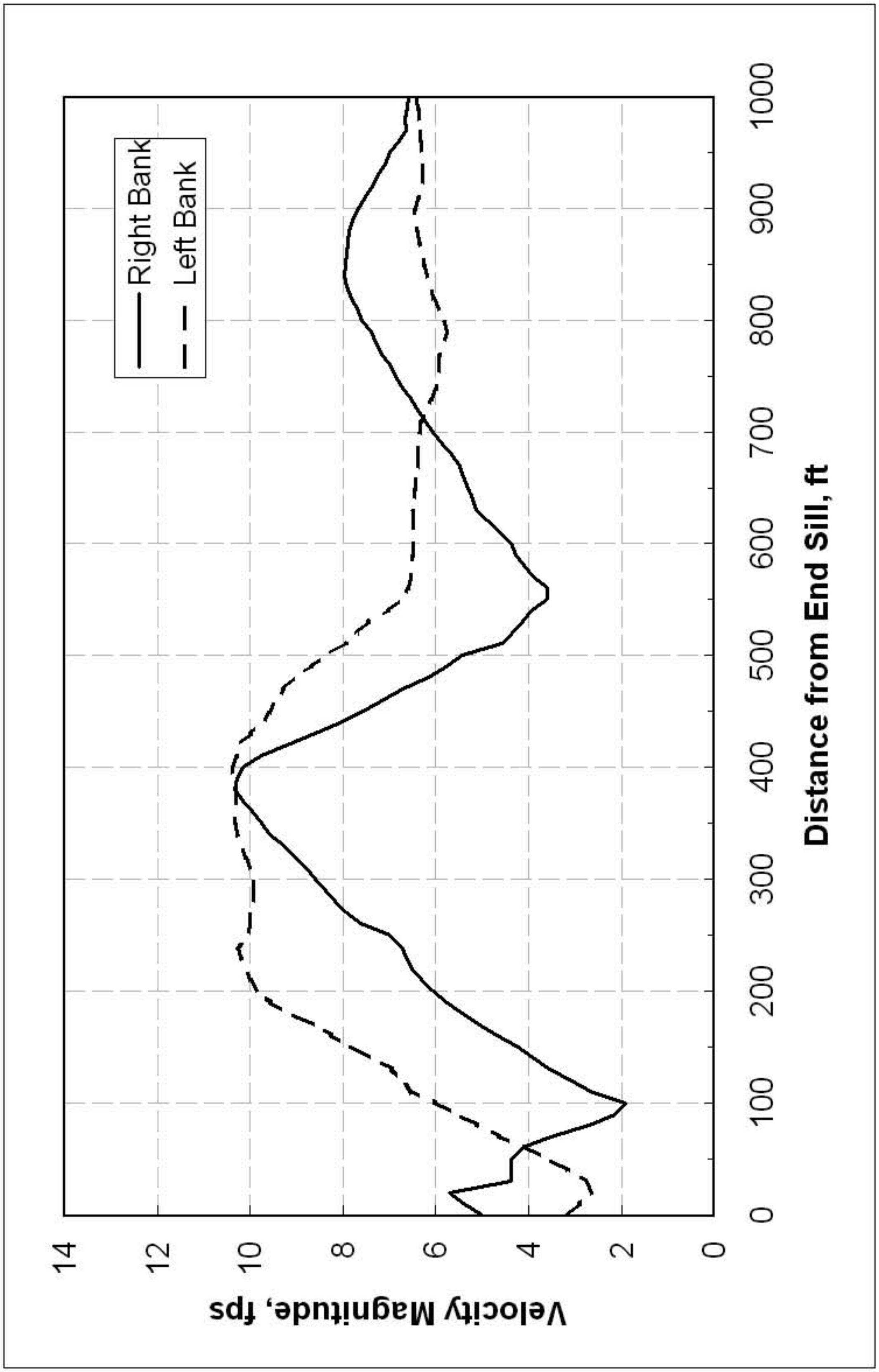

Figure 41. Velocity magnitude profile at el 889, Condition 6, discharge 207,000 cfs, stilling basin tailwater el 907.0 (left and right are referenced to looking downstream).

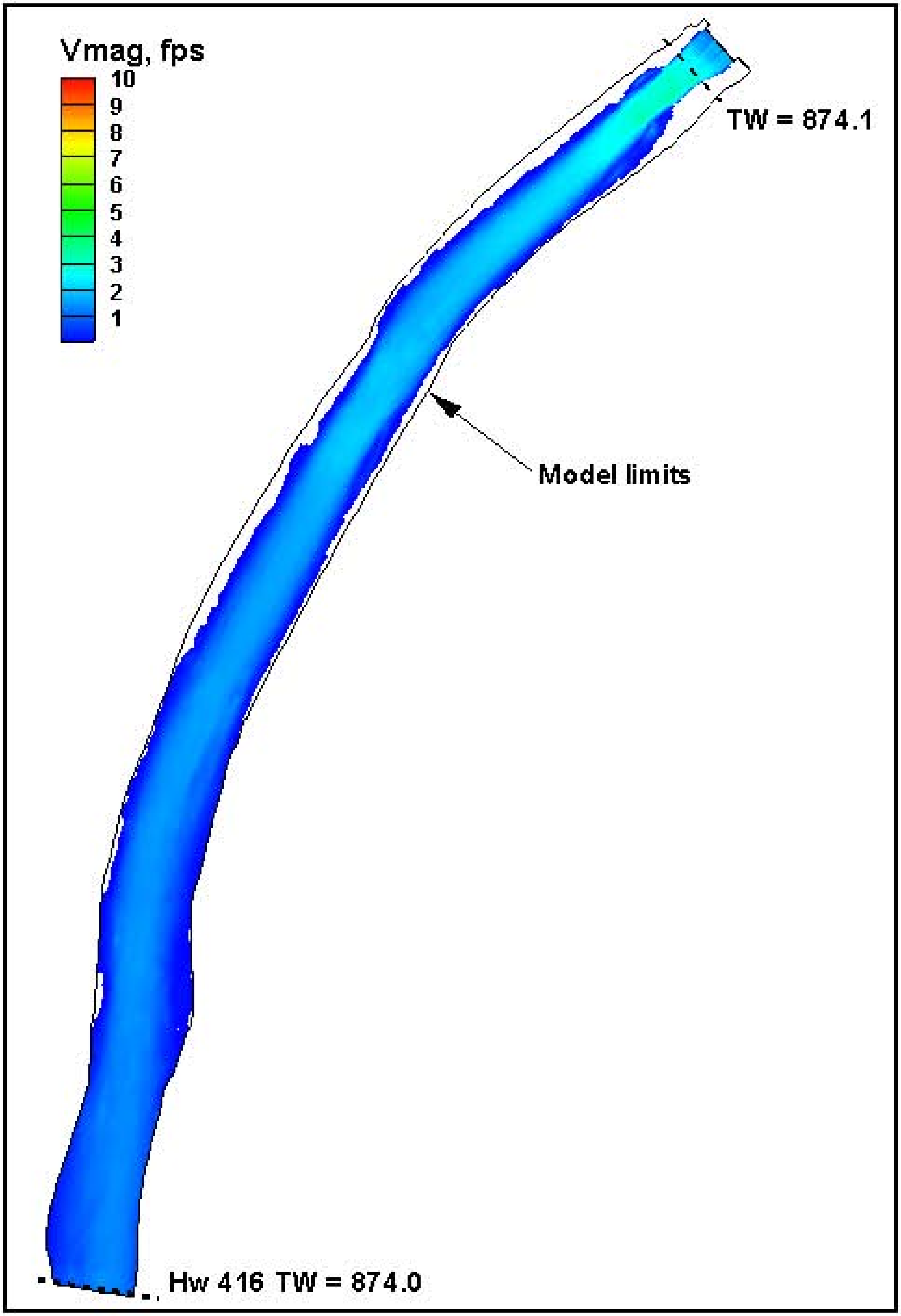

Figure 42. Velocity magnitude contours, Condition 7, discharge 8,900 cfs, stilling basin tailwater el 874.1.

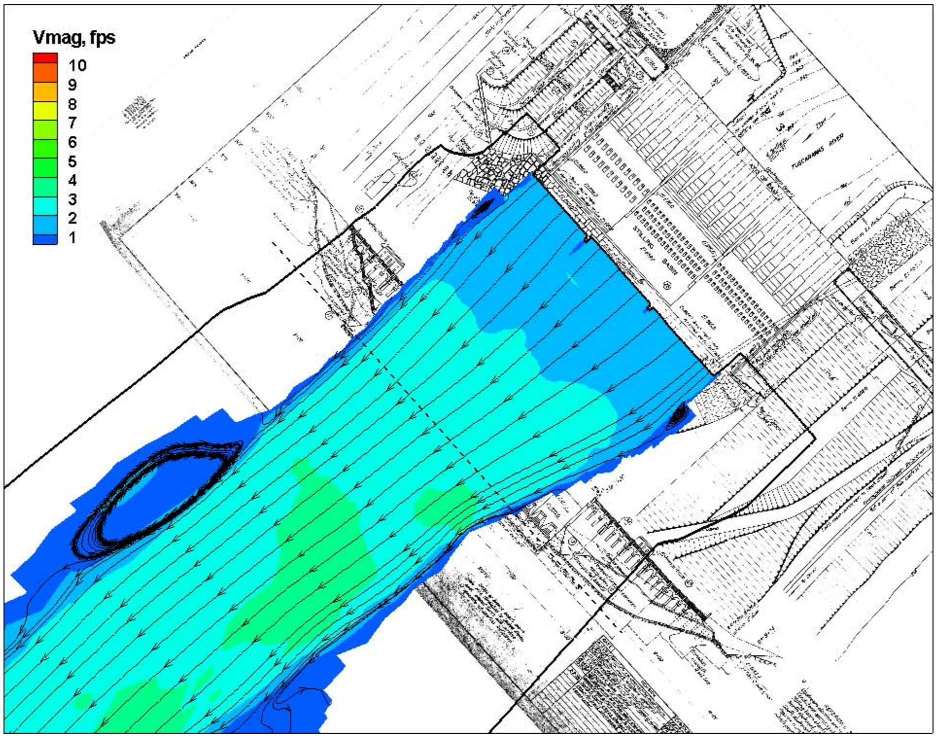

Figure 43. Velocity magnitude contours and stream traces downstream of Dover Dam, flow Condition 7, discharge 8,900 cfs, stilling basin tailwater el 874.1.

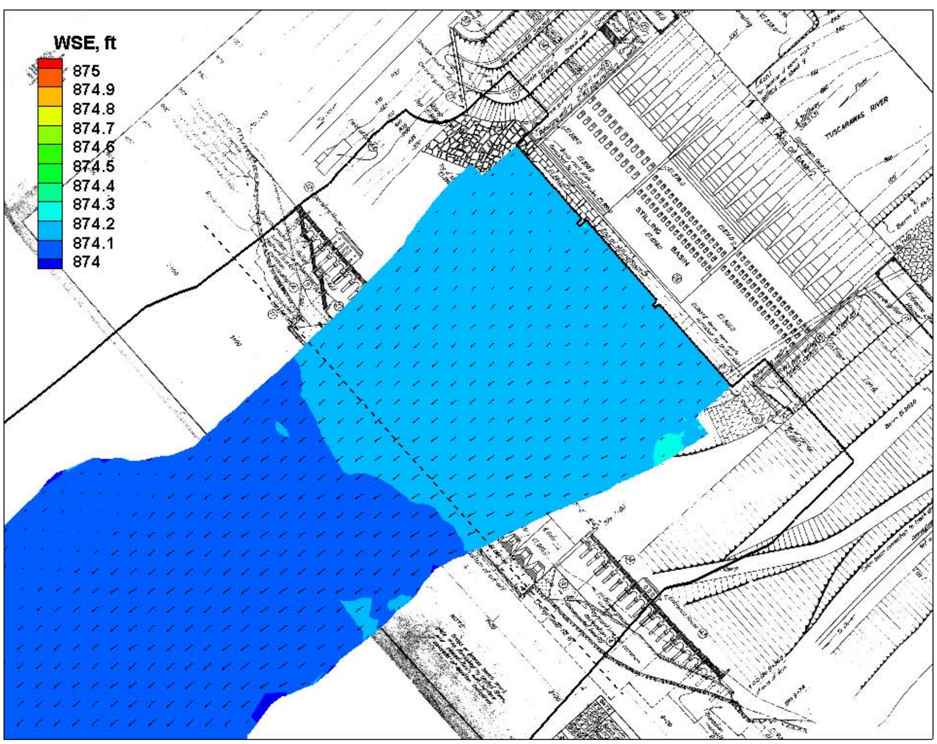

Figure 44. Water surface contours and vectors, flow Condition 7, discharge 8,900 cfs, stilling basin tailwater el 874.1.

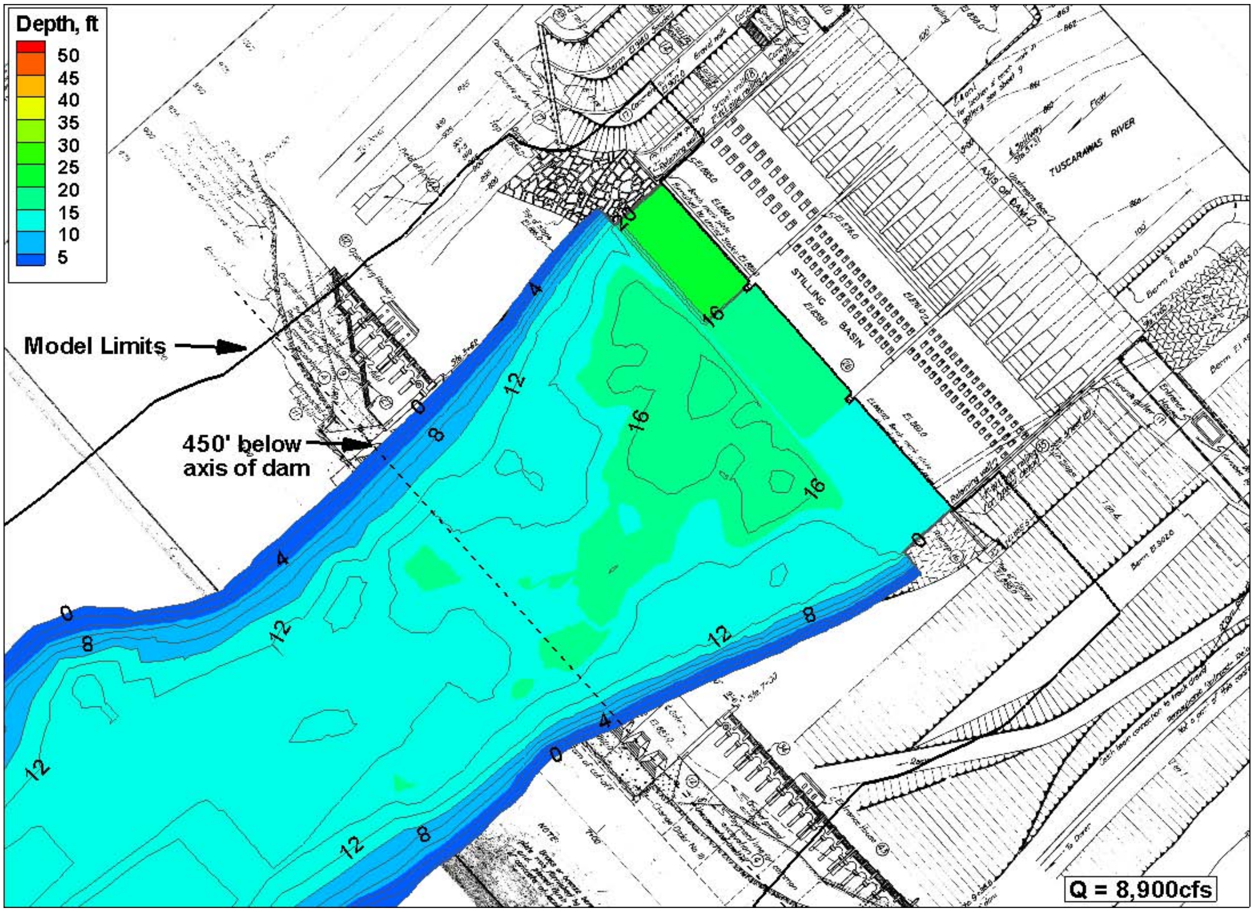

Figure 45. Water depth contours, flow Condition 7, discharge 8,900 cfs, stilling basin tailwater el 874.1.

4 Summary

The U. S. Army Corps of Engineers, Huntington has been charged with upgrading Dover Dam to meet hydrologic design standards and to address stability issues as a part of a safety assurance program. Flow conditions in the Tuscarawas River downstream of the Dover Dam were simulated with the 2D depth-averaged flow code, ADH. These simulations were conducted to determine flow velocities and patterns downstream of the dam during high spillway flows. Discharges ranging from 8,900 cfs to the Probable Maximum Flood of 207,000 cfs were modeled. The highest velocities were associated with the PMF conditions of 207,000 cfs and stilling basin tailwater of el 907.0. Flow along the banks reached 13 fps over some areas and was as large as 8 fps within eddies that set up behind the retaining walls. These flow conditions are likely to cause bank erosion downstream of the stilling basin under existing conditions. Therefore, additional bank protection will be included in the upgrading plans. District engineers will use information gathered from this study to design bank protection below the dam.

References

Huntington District, US Army Corps of Engineers (2007). Dover Dam Muskingum River Basin, Ohio, Dam Safety Assurance Program Final Evaluation Report and Environmental Impact Statement.

Tate, J. N., Berger, R. C. and Stockstill, R. L. (2005). “Refinement indicator for mesh adaption in shallow-water modeling,” *Journal of Hydraulic Engineering*, Vol. 132, No. 8, pp. 854-857.

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
September 2009	Final report	

4. TITLE AND SUBTITLE

Numerical Model Study of the Tuscarawas River Below Dover Dam, Ohio

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

Richard L. Stockstill and Jane M. Vaughan

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

U.S. Army Engineer Research and Development Center
Coastal and Hydraulics Laboratory
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

8. PERFORMING ORGANIZATION REPORT NUMBER

ERDC/CHL TR-09-17

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

U.S. Army Engineer District, Huntington
502 8th Street
Huntington, WV 25701-2070

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

The U. S. Army Corps of Engineers, Huntington District (LRH) has been charged with upgrading Dover Dam to meet hydrologic design standards and address stability issues. The LRH requested that the U. S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory (CHL), evaluate the flow conditions in the Tuscarawas River downstream of Dover Dam as part of a safety assurance program. The two-dimensional depth-averaged module of the Adaptive Hydraulics (ADH) finite element flow solver was used to obtain velocity information and water-surface elevations. This report provides water-surface elevations, velocity data, and flow patterns for flows varying from 8,900 cfs to the Probable Maximum Flood of 207,000 cfs. These flows may cause bank erosion downstream of the stilling basin under existing conditions. District engineers will use the information gathered from this study to design bank protection below the dam.

15. SUBJECT TERMS

Dam safety	Finite element	Shallow-water equations
Dover Dam	Numerical models	Tuscarawas River
	Probable maximum flood	Two-dimensional

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			**19b. TELEPHONE NUMBER** *(include area code)*
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED		58	